

(NASA TMX-50347)

N65-88829

~~X63-15665~~

CODE 2A

68 p.

STATUS OF V/STOL RESEARCH AND DEVELOPMENT

IN THE UNITED STATES

By John P. Campbell

70 refs

NASA Langley Research Center
Langley Station, Hampton, Va., U.S.A.

^{9th}
Presented at the ~~Ninth~~ Anglo-American Conference

Boston, Massachusetts - Montreal, Canada
October 17-22, 1963

Available to NASA Offices and
NASA Personnel

STATUS OF V/STOL RESEARCH AND DEVELOPMENT
IN THE UNITED STATES

By John P. Campbell*

NASA Langley Research Center

SUMMARY

15665

The status of research and development in the United States is reviewed with particular emphasis on significant research results obtained since the last Anglo-American Conference. Research information is presented on the helicopter, on propeller, ducted-fan, and turbojet aircraft, and on V/STOL handling-qualities requirements. A continuing strong research interest is indicated in the helicopter field because of recent developments such as the hingeless-rotor helicopter. The Tri-Service V/STOL transport program is shown to be providing an impetus to research and development on propeller and ducted-fan V/STOL types. Two areas of V/STOL research and development in which it is noted that the United States is lagging are turbojet V/STOL aircraft and V/STOL aircraft engines.

INTRODUCTION

It is the purpose of this paper to review the status of V/STOL research and development in the United States with particular emphasis on significant research results obtained since the last Anglo-American Conference in 1961. Research information will be presented dealing with the helicopter, with propeller, ducted-fan, and jet V/STOL aircraft, and with the general area of V/STOL handling-qualities requirements.

*Associate Chief, Flight Mechanics and Technology Division, Langley Research Center, Langley Station, Hampton, Virginia.

SYMBOLS

A	disk area, sq ft
\bar{c}	mean aerodynamic chord, ft
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$
C_T	thrust coefficient, $\frac{\text{Thrust}}{qS}$
D	diameter, ft
h	height above ground, ft
L	lift, lb
M	pitching moment, ft-lb
q	dynamic pressure, lb/sq ft
r	radial location of a particular station, ft
R	radius of rotor, ft
S	area, sq ft
T	thrust, lb
V	airspeed, knots or ft/sec
W	weight, lb; or airflow, lb/sec
β	propeller blade angle, deg
γ	flight-path angle, deg
δ_f	flap deflection, deg
δ_n	nozzle deflection measured from vertical, deg
ΔT	average temperature rise in fan inlets, $^{\circ}\text{F}$

Subscripts:

j	fan efflux
max	maximum
RPM	fan rpm held constant
s	static condition (zero airspeed)
∞	out of ground effect

HELICOPTER RESEARCH

During the two years since the last Anglo-American Conference, significant results have been obtained in several different areas of helicopter research and development. Some typical examples of this research are covered in figures 1 to 10. Much of the information presented in these figures has been presented in previous papers (refs. 1 to 16) and is presented here in summary form as an indication of the types of research that have been conducted. Subjects covered include the hingeless or nonarticulated rotor, flight measurements of rotor-blade periodic airloads, the rotor-blade stall phenomenon, the height-velocity diagram associated with the so-called "deadman's zone," and the improvement of helicopter performance by drag cleanup.

The Hingeless-Rotor Helicopter

The hingeless-rotor or nonarticulated-rotor principle which has been receiving increasing attention during the last few years offers promise of providing a large step forward toward a simpler, less expensive, and easier-to-fly helicopter. The hingeless-rotor principle has sometimes been referred to as the rigid-rotor principle because the blades are attached directly to the hub without either flapping or lag hinges and the hub is rigidly attached to the rotor drive

shaft. The use of the term "rigid" in describing the system is not considered desirable, however, because an essential feature of a successful system of this type appears to be the incorporation of adequate flexibility into the blade itself. As pointed out in reference 1, most and perhaps all of the past failures with "rigid" rotor systems involved attempts to increase the rigidity of the blade as well as its attachment to the rotor shaft. On the other hand, the success of current hingeless-rotor systems results from the fact that no attempt is made to eliminate flexibility but rather that varying amounts of flexibility are used as means of alleviating the high stress levels in the rotor system.

Most of the recent research and development on the hingeless-rotor principle has been carried out by Lockheed Aircraft Corporation, Bell Helicopter Company, and the NASA. Lockheed, which has chosen the hingeless-rotor helicopter as its entry into the helicopter field, is involved in the development of what is intended to be an optimized operational aircraft of this type. After initial work with a simplified machine starting in 1959, Lockheed built the XH-51A shown in figure 1 under a joint Army-Navy contract and has almost completed the contractor's flight tests before turning the helicopter over to the Navy for service evaluations. In addition, as part of this program, wind-tunnel research on a full-scale rotor system has been conducted in cooperation with the NASA in the Ames Research Center 40- by 80-foot tunnel. (See refs. 3 and 4.)

Bell's work on the hingeless-rotor principle (ref. 5) has involved the use of special rotor systems installed on existing helicopters to provide research information. One of these hingeless-rotor systems was obtained by the NASA Langley Research Center and installed on an Army H-13 helicopter for some exploratory research on the hingeless rotor at Langley. A photograph of this machine is presented in figure 2. It should be pointed out that this particular

hingeless-rotor arrangement does not appear to be very clean and simple because it was fabricated from off-the-shelf components and experimental hub components which were oversized to provide generous margins of safety.

Some of the research results obtained with the helicopter shown in figure 2 are presented in figures 3 and 4. These figures, which were taken from reference 7, illustrate the inherently good control response and handling qualities of the hingeless-rotor helicopter and show a sample of structural loads information dealing with a possible problem for helicopters of this type.

The left-hand plot of figure 3 consists of a time history of the pitching velocity produced by a longitudinal-control step input in hovering flight for the hingeless-rotor helicopter of figure 2 compared with a typical response for a conventional hinged-rotor helicopter. The response for the hingeless rotor is much more rapid than that for the hinged rotor. As a result of this "tight" response, the pilot of the hingeless-rotor machine receives early and clear evidence of the angular velocity developed by the control. In contrast, the much slower response for the hinged-rotor case requires that the pilot wait a much longer time before he can judge the resulting steady-state angular velocity.

In the right-hand plot of figure 3, the control power and damping of the hingeless-rotor helicopter are shown, together with the military handling-qualities boundaries. Also shown for comparison in the lower left-hand corner of the plot are the combinations of control power and damping of conventional hinged-rotor helicopters used in previous NASA flight investigations. It is apparent that the hingeless-rotor helicopter meets the minimum requirements and also that it possesses values of control power and damping several times greater than values for conventional helicopters.

One of the primary objectives of the NASA flight program with the hingeless-rotor helicopter of figure 2 was to obtain samples of loads experienced in flight under practical conditions and to determine which of the conditions required most immediate and detailed study of loads and dynamics. (See ref. 7.) An example of flight-loads measurements during a hovering maneuver in which the pilot performed a longitudinal-control step displacement and recovery is presented in figure 4. The large buildup of cyclic chordwise bending moments appears to be primarily a function of angular velocity. During the initial portion of the maneuver, the rotating mast moments do not build up because the initial control moment cancels a moment due to some minor center-of-gravity offset. During the recovery when the control moment and the offset center-of-gravity moment add, however, the cyclic mast moments reach a maximum at maximum angular acceleration. It appears from this result that the allowable center-of-gravity travel of the hingeless-rotor helicopter may tend to be restricted by maneuver loads.

In the NASA hingeless-rotor flight study, the structural loading problem of most concern proved to be the "in-plane" or chordwise bending moments induced in the rotor blade. A promising method of solving this problem was indicated in the results of a wind-tunnel program on a 10-foot-diameter hingeless-rotor dynamic model conducted at the NASA Langley Research Center as a cooperative effort of NASA, Lockheed, and the Army. This program included a study of the influence of blade stiffness ratio on blade structural loads. The blade stiffness ratio refers to the ratio of the blade bending stiffness in the chordwise direction to that in the flapwise direction. Conventional blades, which are very stiff in the chordwise direction and quite flexible in the vertical direction, have a very high stiffness ratio which results in the coupling of blade bending deflections with blade twist. This coupling can be reduced by reducing the blade chordwise

stiffness and can be theoretically eliminated by matching the chordwise stiffness to the flapwise stiffness. Figure 5 presents wind-tunnel data which indicate that the reduction of blade chordwise stiffness can lead to a significant reduction in chordwise structural loadings. The data show a large increase in chordwise cyclic load with increasing speed for the conventional blade (that is, for the blade with high chordwise stiffness and low flapwise stiffness). By modifying the attachment of the blade at the root to reduce the chordwise stiffness to equal the flapwise stiffness, a large reduction in the chordwise cyclic loads over the entire speed range was obtained. An even greater reduction in loads was obtained by matching the chordwise and bending stiffness at all points along the blade radius. The results presented in figure 5 are for steady 1 g flight. Similar improvements in chordwise cyclic loads were obtained in tests in which the load factor was increased to about two.

In general, the wind-tunnel and flight research carried out to date on the hingeless-rotor principle has been very encouraging and has indicated definite promise of improvements to be obtained by application of the principle.

Rotor-Blade Periodic Airloads

Some interesting information regarding rotor-blade periodic airloads has been obtained recently in a flight investigation carried out at the NASA Langley Research Center with an H-34 helicopter instrumented to measure rotor-blade pressure distributions. (See refs. 1, 2, 8, and 9.) A sample of the data obtained is presented in figure 6. Measured blade loads for different azimuth positions are shown and the theoretical variation of the blade loads for the same test condition is also presented for comparison. It is apparent that there are definite disagreements between experiment and simple theory, particularly in the existence

of "jumps" or abrupt changes in the experimental data. These jumps appear in the data for all conditions except at the higher speeds and are generally most pronounced in the vibration-critical flight conditions. Thus, an understanding of the source of these jumps may lead to a better understanding of the basic problem of helicopter vibration and periodic airloads.

A simple physical picture of the probable source of the jumps in the experimental data is presented in figure 7. The sketch shows how a given blade, in three successive positions, encounters the tip vortex generated by the preceding blade and does so at successively smaller radii through this portion of each revolution. The azimuth values predicted for the load jumps by this simple geometrical relationship are shown by the ticks in figure 6. The fact that the ticks are somewhat closer together than the measured jumps is attributed to a rolling-up and inward shift of the tip vortex (whereas fig. 7 was drawn on the basis that the vortex center stays on the line traced by the path of the tip). Several organizations are now studying possible methods for predicting the magnitude and location of these jumps.

Rotor-Blade Stall Phenomena

A wind-tunnel investigation has recently been completed at the NASA Langley Research Center in which a 15-foot-diameter rotor was operated at extreme thrust coefficients and high tip-speed ratios to provide information on rotor-blade stall phenomena in high-speed flight. (See ref. 10.) The results indicated that the loss in rotor lift for conditions in which large regions of blade stall were expected was much less than anticipated for the range of conditions covered. The data of figure 8 taken from reference 10 illustrate this point. Measured rotor thrust, in terms of hovering mean lift coefficient, is compared with calculated

values of thrust based on a simple theory using constant lift-curve slope and on a more refined theory utilizing two-dimensional section characteristics of the rotor blade. It can be seen that both calculations agree with the theory up to the point at which the stall is theoretically predicted. At the higher lift coefficients, the simple theory overpredicts the lift while the refined theory underpredicts it, with the simple theory giving the closer agreement.

In the past, somewhat similar cases of disagreement between experimental data and the refined theory have been noted, but usually with smaller models and at much lower Reynolds numbers. The 15-foot-diameter rotor used in these tests should be expected to provide results generally applicable to small helicopters, and analysis has indicated that similar trends should also be expected in varying degrees with larger helicopters. (See ref. 10.)

The Helicopter Height-Velocity Diagram

A cooperative research program is being conducted by the Federal Aviation Agency (FAA) and the NASA to establish methods for determining the proper height-velocity diagram for safe autorotative landings for a helicopter operating at density altitudes other than the one at which its flight-test program for certification was conducted. The first portion of this program consisting of autorotation flight tests of a Bell 47G-3B helicopter at various altitudes and gross weights has been completed by the FAA and is reported in reference 11. A sample of the data obtained is presented in figure 9. The left-hand plot of this figure consists of a plot of height against airspeed for the helicopter at a gross weight of 2,650 pounds and at various density altitudes of the airport. Combinations of height and airspeed to the right of the appropriate curve on the plot represent

initial conditions from which the pilot could make safe autorotational landings - that is, landings in which at least a small amount of usable reserve energy in the form of rotor speed or airspeed is remaining at touchdown. With increasing altitude, there is, of course, an increase in the so-called critical airspeed - the airspeed above which an autorotative landing can be made from any height after power failure in low-speed flight. The right-hand plot of figure 9, which was obtained by crossplotting the data from the left-hand plot and other similar data, shows that there is a straight-line variation of critical airspeed with altitude over the range of parameters covered. The data also indicate a direct variation of critical airspeed with gross weight. Other results brought out in reference 11 show that the maximum safe low hover height (usually designated h_{max}) varies directly with weight or altitude while the minimum safe high hover height (usually designated h_{min}) varies as the square of the critical velocity for the range of parameters covered.

The NASA Langley Research Center is presently engaged in the second phase of this program which involves a digital computer study to develop a generalized analytical procedure for determining the effects on the height-velocity diagram of such parameters as density altitude, rotor stored energy margin, and other geometric and aerodynamic characteristics.

Helicopter-Drag Cleanup

In an effort to obtain increased performance from existing and proposed helicopters, a number of helicopter-drag cleanup investigations have been conducted recently by the Army, Navy, NASA, and industry. (See refs. 12 to 16.) In one example of this work, Bell conducted an investigation on a UH-1B helicopter under an Army contract, with the NASA providing research support by testing the

helicopter in the Ames Research Center 40- by 80-foot wind tunnel. Major modifications to reduce the drag of the helicopter included using a tilting pylon, adjustable in flight, to keep the fuselage in a minimum drag attitude; installing fairings around the pylon, on the landing gear, and just aft of the cargo compartment on the fuselage; installing improved engine inlets; and increasing the vertical fin area and adding camber to the surface. The effect of these changes on performance as determined in flight is shown in figure 10 which was taken from reference 15. The top speed was increased from about 120 to 155 knots. In addition, the range was increased by 30 percent and the vibration level and blade vibratory stresses were appreciably reduced. These pronounced improvements in performance and reduction in vibration problems obtained by modifying an existing helicopter certainly suggest that increased attention to these items in initial helicopter design would pay substantial dividends.

PROPELLER V/STOL AND STOL AIRCRAFT RESEARCH

A substantial research effort in the propeller V/STOL and STOL area has continued during the past two years (refs. 17 to 32) with much of the research being directed toward the wing stall and related problems encountered in transition or low-speed flight. The awarding of a contract for the construction of the XC-142 Tri-Service V/STOL airplane shortly before the last Anglo-American Conference marked a turning point in the development of the tilt-wing V/STOL aircraft type. The research and development effort in this general area took on more significance and much of the effort was oriented to provide direct support for the XC-142. An extensive wind-tunnel program was undertaken by the contractor (Vought-Hiller-Ryan) and the NASA to provide detailed information on the

configuration and to refine the design. Photographs of two of the models used by the NASA in this work are presented in figures 11 and 12.

Another interesting propeller V/STOL development is the Curtiss-Wright X-19 tandem four-propeller airplane which has been built as part of the Tri-Service V/STOL transport program and which is now undergoing testing by the contractor. Only a limited amount of research has been carried out on this tilt-propeller type, with much of it being done by Curtiss-Wright while the airplane was a company project intended for development as a civil transport. The NASA Langley Research Center has recently conducted a general research wind-tunnel study to provide some basic aerodynamic information on the tilt-propeller type. (See refs. 17 and 29.) Results of this study indicate rather poor STOL performance for the tilt-propeller type compared to that of a well-designed tilt-wing configuration. On the other hand, the tilt-propeller type appears to have a less serious wing-stall problem in transition than the tilt-wing type.

In order to provide flight information more directly applicable to the XC-142, the VZ-2 tilt-wing research airplane which has been used in research at the NASA Langley Research Center for several years (ref. 18) has been modified to incorporate full-span flaps and ailerons (ref. 19). Research is now in progress with these modifications. Results to date indicate a substantial improvement in the wing-stall problem in transition flight with the full-span flap programed to deflect with changes in wing incidence. This result is illustrated in figure 13 which compares the pilot's opinion of the flying qualities of the VZ-2 with the flap installed with previous results obtained with the plain wing and with leading-edge droop. The leading-edge droop had been found to provide a definite improvement in flight characteristics as indicated by the upper and lower left plots of figure 13 which show the greater permissible rates of descent with the

droop. An even more pronounced improvement was obtained with the trailing-edge flaps (leading-edge droop removed), as shown by the plot at the lower right. The improvement was especially noticeable at the higher speeds (50 to 70 knots). Although the permissible rate of descent was greatly increased at these higher speeds when the flaps were installed (as indicated by the lower position of the boundary), there was a mild buffet problem for some conditions falling on the acceptable side of the boundary.

The use of differential deflection of the ailerons on the VZ-2 as the only source of yaw control in hovering flight appeared marginal out of ground effect and inadequate in ground effect. In landings, performed with high wing angles (65° and 55°) and at low airspeeds, an unfavorable ground effect was experienced which caused the airplane to sink rather rapidly from heights of about 10 feet.

Some wind-tunnel data on the wing-stall problem of a tilt-wing V/STOL configuration in and out of ground effect are presented in figure 14. The curves shown in this figure represent combinations of airspeed and rate of sink at which $C_{L_{max}}$ occurs and therefore roughly correspond to the right-hand portion of the flying-qualities boundaries of figure 13. Data are shown for a small model in and out of ground effect and for a large model in a test section which may not have been large enough to avoid some ground effect. (See fig. 11.) The data have been scaled to represent an airplane with a wing loading of 50 pounds per square foot in order to be roughly comparable to other data to be presented later. The small-scale data indicate no effect of the ground at speeds above about 50 knots. At lower speeds, however, there is a detrimental ground effect as evidenced by the upward shift of the stall boundary. (Satisfactory or unstalled conditions are above and to the right of the boundary.) For example, at an airspeed of 30 knots and for the level-flight condition (zero rate of sink), the

data indicate a satisfactory condition out of ground effect but an unsatisfactory condition in ground effect. The boundary for the large-scale model is approximately parallel to that for the small model in ground effect, indicating that the large-scale model may be experiencing some detrimental ground effect in the normal test location in the tunnel at the lowest speeds and highest power conditions. Other data (not presented) show that the large model, like the small model, had a more severe wing-stall problem when it neared the ground.

One method of alleviating the stall problem in transition or landing approach for propeller V/STOL and STOL airplanes involves the use of differential blade pitch between the inboard and outboard propellers. This feature, which was proposed several years ago by Breguet in conjunction with their STOL airplane development, was investigated on the XC-142 model shown in figure 11. (See ref. 20.) Some results of this study are presented in figure 15 in the form of $C_{L_{max}}$ boundaries similar to those of figure 14. Boundaries are shown for the normal case of 10° blade pitch on all propellers and for the case of differential pitch with the inboard propellers at 14° and the outboard propellers at 0° . The shift in the boundaries indicates a pronounced beneficial effect of differential thrust which amounts to approximately a 700-foot-per-minute greater permissible rate of descent at a given speed or to a 10-knot decrease in stall speed at a given rate of descent. Despite the fact that the outboard propeller was producing a net negative thrust in the differential pitch case, the outboard portion of the wing did not stall prematurely. Apparently, the inner portion of the outboard propeller was actually producing positive thrust and therefore an increment of positive slipstream velocity over most of the outboard portion of the wing. Although the outer portion of the propeller was producing negative thrust, the regions of

negative thrust occurred either where the propellers overlap or where the propeller extends beyond the wing tip. (See ref. 20.)

Past research has established the importance of wing size and flap effectiveness on the wing stall of propeller V/STOL aircraft in transition, and particularly in descent conditions. The amount of wing and flap required to avoid stalling has not been very clearly established, however, and no really satisfactory method of analysis of the wing-stall problem has been developed. (See ref. 21.) An analysis of existing wind-tunnel and flight data has been made in an effort to provide at least a first approximation to the proper wing size to avoid wing stalling and the relationships obtained are shown in figure 16. This figure, which was taken from reference 21, shows the effect of wing-chord-to-propeller-diameter ratio on the permissible angle of descent for propeller V/STOL aircraft. This chart is admittedly an oversimplification of the problem and applies only to wings with a fairly large and elaborate flap system. The explanation for the data points is given by the powered-model lift-drag sketch at the upper right of the figure. A broad-brush handling-qualities boundary has been drawn between the two sets of data based partly on results obtained with the VZ-2 airplane and partly on the assumption that some local wing stalling could be tolerated but that complete wing stall could not. The plot indicates that satisfactory conditions in level-flight transition could be obtained with an extended chord-diameter ratio of about 0.3 to 0.5 but that a 10° descent requirement calls for an extended chord-diameter ratio of about 0.6 to 0.8.

Some pertinent information on the effects of wing stall on propeller V/STOL and STOL aircraft is presented in figure 17 which was taken from reference 20. In this figure the approach speeds chosen by pilots of three STOL aircraft - BLC-130, Breguet 941, and Ryan VZ-3 - are shown on a plot similar to that used in

figures 13, 14, and 15. Also presented for comparison are similar data for an airplane with conventional high-lift devices. The approach speeds and rates of descent shown have all been adjusted to represent a wing loading of 50 pounds per square foot to afford a more direct comparison of the data. The Ryan VZ-3 curves are shown in dotted form because a rather large adjustment from 23 to 50 pounds per square foot was required in this case. The speeds shown are not stall speeds but are approach speeds which were generally at least 10 knots above the stall and which included a sufficient margin to make power changes to correct flight path and also included an allowance for gusts and a provision for flaring. (See ref. 20.) It can be seen from figure 17 that the combined use of slipstream with BLC or large-chord flaps (BLC-130 and Breguet 941) provided approach speeds of about 60 to 70 knots compared to 80 to 90 knots for the airplane with conventional high-lift devices. The VZ-3 airplane, which had a thrust-weight ratio greater than one and a very large flap designed to provide vertical take-off and landing capability, had even lower stall speeds particularly with the leading-edge slat installed.

Most propeller STOL and V/STOL aircraft have experienced some form of lateral-directional problem in low-speed flight which has been considered objectionable or unsatisfactory by the pilot. In some cases, poor lateral-directional characteristics at approach speeds have reduced the controllability and therefore limited the usefulness of the aircraft. Reference 20 points out that such problems have been encountered with the YC-134, BLC-130, and Ryan VZ-3 in flight research at the NASA Ames Research Center. An example of a problem of this type on the BLC-130 in which reduced controllability was exhibited during STOL approaches by large sideslip excursions when maneuvering is illustrated in figure 18, taken from reference 20. The solid lines represent flight data for the

BLC-130 during a banked turn at 65 knots. The data show that when the airplane is banked to initiate a turn, large sideslip angles build up prior to the development of a rate of turn. Actually, the airplane turns initially in the wrong direction because of adverse aileron yawing moments. A simulator study was undertaken to determine the important parameters involved in this case and to seek practical solutions. (See ref. 22.) This study indicated that satisfactory characteristics could be obtained when the static directional stability was increased fourfold and the damping in yaw sixfold, but such large changes would be very difficult to obtain on the BLC-130. A more practical solution indicated by the simulator study was to add damping proportional to rate of sideslip $C_{n\dot{\beta}}$ in addition to doubling the static directional stability. The dotted curve of figure 18 shows the beneficial effect of such a change on the response of the BLC-130 to an aileron input. The sideslipping was greatly reduced and the lag in developing a turn in the proper direction was cut down. Flight tests of the BLC-130 with this modification are now being made to verify the results of the simulator study.

RESEARCH ON DUCTED-FAN V/STOL AIRCRAFT

Most of the recent research on ducted-fan V/STOL aircraft has been directed toward the fan-in-wing and tilt-duct types, and advanced research aircraft of these two types are now under construction. The XV-5A fan-in-wing research airplane is being built for the Army by General Electric and Ryan and the X-22A quad-duct airplane is being built by Bell Aerosystems as part of the Tri-Service V/STOL program.

Fan-in-Wing and Fan-in-Fuselage Research

Extensive large-scale research on fan-in-wing and fan-in-fuselage configurations has been conducted as joint NASA-General Electric projects in the NASA Ames 40- by 80-foot wind tunnel during the last few years. (See refs. 33 to 40.) Some of the more significant results of this research are summarized in figures 19 to 22 which were taken from references 35 and 36. Data are presented for the three configurations shown by the sketches of figure 19: a fan-in-fuselage type (model 1) and two fan-in-wing types (models 2 and 3). Model 3 was intended to provide a fairly close approximation to the XV-5A fan-in-wing research airplane.

Typical variations of lift-thrust ratio with flight-velocity ratio for the three models are presented in figure 19. The total lift increased with increasing speed for all configurations. In some small-scale model tests of similar configurations, a reduction in lift or "lift droop" has been noted at the lower speeds. The discrepancy between the large-scale and small-scale data has not yet been fully explained but at least two factors appear to be involved: a scale effect resulting from the low Reynolds number of the small model tests and a possible tunnel-wall effect on the large-scale data because of the large size of the model relative to tunnel test-section size. The variation of fan thrust with velocity ratio is also shown in figure 19. The increment between fan thrust and model lift shown in the three cases is about 80 percent induced lift due to fan operation and 20 percent due to wing camber. The fact that the induced lift for model 3 is much less than that for models 1 and 2 indicates that an increasing ratio of fan area to wing area results in smaller induced lift. The data presented in figure 19 are for flaps retracted. Data of reference 35 show that trailing-edge flaps behind the fans provide a further increase in lifting capability.

The pitching moments in transition flight for models 1 and 2 are shown in figure 20. In order to allow direct comparison of the data for the two models the moment has been divided by the weight and fan diameter. The moment is much greater for the fan-in-fuselage model (model 1) because the greater depth of the fan results in a larger horizontal force couple produced by the ram drag on the fan inlet and thrust from the fan exit. Trailing-edge-flap deflection reduced the moment variation with speed for model 2 because of the nose-down moment of the flap itself and the reduction of power required.

The effect of ground proximity on hovering lift for models 1 and 3 with the fans operating at constant rpm is shown in figure 21. The fan-in-fuselage model (model 1) had an adverse ground effect amounting to a 23-percent loss in lift at a height of one fan diameter. Loss in fan thrust accounted for 14 percent of the loss while downward aerodynamic forces on the model produced the other 9 percent. The fan-in-wing model (model 3) showed essentially no ground effect since an upward lift on the model airframe compensated for a loss in fan thrust. More information on this ground-effect phenomenon is presented in reference 41.

The problem of reingestion of hot exhaust gases proved to be a definite problem with model 3 when hovering in light winds or in forward flight. The flow patterns involved in these cases are illustrated in figure 22(a), with the shaded areas representing the hot exhaust gas from the turbine. The sketch at the top shows the flow pattern in hovering flight with the model headed into a light wind. In this case, the hot gas was blown back into the vicinity of the model, resulting in a small temperature rise (less than 10° F) in both the fan and gas generator inlets. With forward speed, the hot-gas ingestion problem became more severe because, as the sketch at the lower left of figure 22(a) indicates, there was a shorter path of the hot gases from the turbine exit to the inlet and therefore

less time for the exhaust to cool. For the 60-knot airspeed condition, a temperature rise of 50° F occurred in the fan inlet. When louvers were used to deflect the fan turbine exhaust 30° rearward, the reingestion of exhaust gases was eliminated, as indicated by the flow pattern at the lower right of figure 22(a). Experimental data showing the average temperature rise in the fan inlets for several ground heights and vector angles as a function of velocity ratio are presented in figure 22(b). It can be seen from the left-hand plot that increasing the height above the ground decreased the velocity range for ingestion but did not greatly change the maximum temperature rise. The largest temperature rise shown produced a thrust loss which would require a 4.5-percent increase in fan speed to offset the loss. The right-hand plot shows the pronounced beneficial effect of vectoring the fan turbine exhaust rearward. The data shown in figure 22(b) are for temperature rise in the fan inlet. The gas generator inlets on top of the fuselage experienced less ingestion with a maximum temperature rise of 20° F being measured.

In general, the tests in the Ames 40- by 80-foot wind tunnel of the large model similar to the XV-5A airplane (model 3) have indicated that the airplane should have static stability and should be controllable throughout the transition range. Flight tests of a 0.18-scale model of the airplane in the NASA Langley full-scale tunnel have also given a preliminary indication of generally satisfactory static and dynamic stability characteristics in the transition.

Tilt-Duct Research

Research on tilt-duct V/STOL aircraft has, during the last 2 or 3 years, shifted from two-duct configurations such as the Doak VZ-4 research airplane to tandem four-duct configurations such as the Bell X-22A airplane. (See refs. 42

to 45.) Much of the research at present is in direct support of the X-22A. NASA is providing some of this support with static wind-tunnel investigations of small-scale and large-scale models and with dynamic stability and control studies with a free-flying model.

An investigation of operational downwash impingement problems of the tandem four-duct type is being carried out by Kellett Aircraft Corporation under contract to the Navy. In this investigation, a large semispan test setup (approximately a full-scale model of the X-22A) is being tested over various types of terrain and water at disk loadings up to 60 pounds per square foot. In general, the results to date indicate some rather serious impingement and recirculation problems. A sketch of the basic recirculation flow field in hovering determined in the Kellett investigation is presented in figure 23. One area of flow of particular concern is the upwash area between the front and rear ducts near the sides of the fuselage. This upflow can cause large amounts of debris to be blown up above the fuselage and thereby lead to particle ingestion problems. Research is in progress to determine means of alleviating these problems.

Some large-scale and small-scale wind-tunnel research on single ducted fans has been conducted by the NASA and reported in references 46 to 50. One example of the results of this research is presented in figure 24. Information regarding duct inlet stall is shown on a plot of duct angle of attack against flight speed. The solid line represents the angle-of-attack variation for the ducts of the Doak VZ-4A airplane for the steady level-flight condition. The duct stall boundary for the VZ-4A shows a minimum duct stall margin of about 8° at 40 knots air-speed, which indicates that the duct could stall in decelerating flight. For tilt-duct configurations with higher disk loadings, the stall margin would probably be greater than that shown for the VZ-4A.

TURBOJET V/STOL AIRCRAFT RESEARCH

United States effort in the turbojet V/STOL area has been overshadowed during the last few years by the progress in Europe toward the development of operational turbojet V/STOL aircraft. The early lead in research and development in this area resulting from the work associated with the Ryan X-13 and Bell X-14 research airplanes was soon lost when work on the Bell D-188A fighter airplane was discontinued in 1959 and no work on other operational turbojet V/STOL aircraft was started. (See ref. 51.) The only new turbojet V/STOL aircraft in this country is the Lockheed XV-4A, a small research aircraft making use of the jet ejector principle. (See ref. 52.) The XV-4A is now being flight tested by the contractor. The Bell X-14A is still being used in research at the NASA Ames Research Center but this work is in the general area of handling-qualities requirements and not directed specifically toward turbojet V/STOL aircraft.

Although a number of small-scale wind-tunnel studies have been carried out on turbojet V/STOL configurations, much of this work has been classified or proprietary. References 53 to 56 cover the results of some unclassified research in the general area of induced interference effects and figures 25 and 26 present some results of more recent research in this area.

Figure 25 shows the effect of nozzle configuration on the lift and pitching moment of a turbojet V/STOL model in the transition range of flight. Nondimensionalized lift- and pitching-moment data are plotted against velocity ratio for three nozzle configurations: a single large nozzle and two arrangements of four small nozzles. All three configurations show the typical lift loss at zero angle of attack and nose-up pitching moments resulting from negative pressures induced on the lower surface of the fuselage and wing behind the jets. (See refs. 53 and 56.) The configuration at the right with the four nozzles arranged in a

diamond pattern appears to be the best of the three since it produces smaller nose-up pitching moments and greater lift for a given angle of attack and velocity ratio. The better characteristics of this configuration are attributed to the more effective "streamlining" of the jet exhaust pattern with the diamond arrangement and therefore smaller negative pressures induced on the lower surface of the fuselage and wing behind the jets. It has been shown in related research (ref. 56) that jet exhausts issuing perpendicularly from the lower surface of a plate produce induced interference effects similar to those produced by solid cylinders having the same diameter as the jets. It is therefore reasoned that a more streamlined arrangement of these effective cylinders should produce less obstruction to the flow and therefore less induced effect on the airframe of the model.

An example of jet-induced effects on a different type of V/STOL configuration is presented in figure 26. Pitching-moment data are shown for a vectored-thrust turbofan V/STOL model for various horizontal tail arrangements and thrust conditions. The left-hand plot shows data for the power-off condition with tail off and with the tail in a high and low position. It can be seen that the model is unstable (positive slope of pitching-moment curve) with the tail off and that the instability increases with increasing angle of attack. Addition of the tail in the high position does not entirely eliminate the instability, but moving the tail to the low position (and into a more favorable downwash field) does provide stability over the entire lift range. The plot on the right, which presents data for the power-on condition with the low tail position, shows that large changes in trim and reductions in stability occur when thrust is added with the nozzles in the intermediate angle range (30° and 60°). A highly unstable condition results for the 60° nozzle setting. Analysis has indicated that the detrimental

effects of power are caused by a change in the flow field at the horizontal tail. Apparently, the favorable downwash field existing at the low horizontal-tail position for the power-off condition is shifted downward away from the tail by the strong jet exhaust flow from the deflected nozzles. The problem illustrated by these data appears to be a basic one for vectored-thrust or lift-engine V/STOL fighter configurations having horizontal-tail surfaces. Careful attention must be given to the arrangement of the wing, tail, and nozzles to achieve acceptable longitudinal-stability characteristics for all flight conditions.

RESEARCH ON HANDLING-QUALITIES REQUIREMENTS

A number of research studies directed toward the determination of rational handling-qualities requirements for V/STOL aircraft have been conducted during the last few years and this work is continuing. (See refs. 57 to 70.) Research in this area has been carried out with V/STOL aircraft (usually with variable-stability and control features) and with simulators of various types. A large portion of the handling-qualities research has been carried out by the NASA at its Ames and Langley Research Centers. Langley has used helicopters in most of its flight research along this line and is presently making use of a YHC-1A twin-turbine tandem helicopter equipped with very elaborate variable-stability-and-control equipment and with provisions for conducting research on the problem of making steep approaches under instrument flight conditions. Ames is using the X-14A turbojet V/STOL variable-stability-and-control research aircraft for its flight work in this area. Other research organizations such as Cornell Aeronautical Laboratory and Princeton University and a number of companies have also carried out research on handling-qualities requirements using either helicopters or simulators.

A summary of some of the more recent NASA research on handling-qualities requirements is presented in figures 27 to 30. These figures were taken directly from reference 57 but much of the information presented in the figures had been covered previously in references 58 to 60. All four of the figures consist of plots of rate damping against maximum control power with various boundaries for desired or minimum acceptable handling qualities. In some research studies, the control power per unit control deflection (that is, control sensitivity) has been used instead of maximum control power. There is some disagreement among researchers as to which of these two methods of designating control power is most appropriate for handling-qualities relationships - that is, matching the aircraft to the pilot - and studies are in progress to provide more information on this point.

Results of X-14A flight research to determine desirable combinations of damping and control power about all three axes for the visual hovering task are presented in figure 27. The curves shown represent conditions which were given a rating of 3.5 on the Cooper pilot rating scale. (See ref. 58.) Values of damping and control power to the right of the curves are satisfactory for normal operation while values to the left are only suitable for limited operation. It can be seen from the plot that the pilots required much more damping and control power about the roll axis than about the other two axes. Apparently, pilots are more concerned about lateral positioning and therefore demand increased aircraft response to reduce the time required to correct deviations from a desired position.

More detailed information on the roll-control requirement are presented in figure 28. In addition to the 3.5 pilot rating boundary, the 6.5 rating boundary (minimum acceptable for emergency operation) for the X-14A is shown and lines are

included to indicate the tentative requirement in the AGARD V/STOL handling-qualities recommendations (ref. 61) for a series of gross weights. An additional point is also shown for the Hawker P.1127 with a pilot rating of 3.5. It can be seen that the tentative AGARD recommendation for the X-14A (which weighs 3,800 pounds) falls in a region which the X-14A flight tests indicate would have a rating of between 4 and 5 and would be acceptable only for limited operation. The data indicate that the P.1127 requires about the same control power and damping as the X-14A to obtain a 3.5 pilot rating, whereas the AGARD recommendation indicates that the heavier P.1127 (weight about 12,000 pounds) should require less control power (in terms of radians per second squared). During the development of the P.1127, the roll-control power was increased from about 1 to 2 radians per second squared in order to achieve satisfactory operation. These results indicate that the AGARD recommendations in their present form are not consistent with flight data being obtained on the X-14A and P.1127. On the other hand, results of recent hovering studies by the NASA with the 30,000-pound H-37 helicopter have been in general agreement with the AGARD recommendations and have indicated that a variation in the requirement with weight (or size) is basically sound. More research is needed in this area to resolve these discrepancies. It appears likely that better agreement would be obtained on the basis of control sensitivity than on maximum control power. It has been suggested by some that the variation of the requirement with gross weight should be dropped in favor of a requirement depending on the operational use of the V/STOL aircraft. Perhaps some combination of these two principles will prove to be the most satisfactory solution.

Figure 29 presents information on the longitudinal control requirements for the X-14A together with the AGARD recommendations for the airplane. In contrast

to the roll-control case, the AGARD recommendation calls for much more longitudinal control power and damping than were found to be needed for satisfactory characteristics in the X-14A flight studies.

Results of simulator studies and flight experience on the desired height control and damping parameters for V/STOL aircraft in hovering flight are presented in figure 30. The hatched lines are the boundaries for pilot ratings of 3.5 and 6.5 obtained with the Ames Height Control Apparatus, a new moving base simulator now in use at Ames Research Center. (See ref. 57.) The results obtained with this simulator are in good agreement with limited results previously obtained on another moving-base simulator but are in disagreement with fixed-base simulator results which indicated a requirement for greater control power. The flight data points for the X-14A and Short SC-1 airplanes with a pilot rating of 3 indicate an even smaller control requirement than that determined with the moving-base simulators.

CONCLUDING REMARKS

The status of V/STOL research and development in the United States has been reviewed and a summary of significant recent research results presented. It is apparent from this review that the helicopter continues to be a subject of strong research interest and that propeller and ducted-fan V/STOL aircraft are also receiving increasing attention because aircraft of these types are now being built as part of the Tri-Service V/STOL transport program and other programs. The United States still lags, however, in work on turbojet V/STOL types. Studies of these types are being conducted by research organizations, the services, and industry but research and development in this area cannot proceed at a very great pace without some firm plans for operational turbojet V/STOL aircraft. Perhaps

in the near future this impetus will be provided by service requirements for turbojet V/STOL aircraft to be used in close support operations.

Another area of research and development in the V/STOL field in which the United States is lagging is the propulsion area. Although some development work on turbojet lift engines has been started since the last Anglo-American Conference, there is still an inadequate research and development program for V/STOL aircraft engines in this country. Since really significant advances in V/STOL aircraft performance in the future will depend on improvements in propulsion systems, there is obviously an urgent need for increased research and development effort in this area.

REFERENCES

1. Gustafson, F. B.: Powered-Lift Research at Langley Field. Presented at the Royal Aeronautical Society Rotorcraft Section Meeting, London, England, December 7, 1962.
2. Gustafson, F. B.: Helicopter Design and Capability Trends as Seen From a Research Viewpoint. Presented at the 1962 SAE National Aerospace Engineering and Manufacturing Meeting, Los Angeles, California, October 8-12, 1962.
3. Statler, W. H., Heppe, R. R., and Cruz, E. S.: "Results of the XH-51A Rigid Rotor Research Helicopter Program." American Helicopter Society Proceedings of the Nineteenth Annual National Forum, May 1-3, 1963, Washington, D.C., pp. 119-133.
4. Culver, Irven H.: "Designing the High-Speed Rigid Rotor Helicopter." Astronautics and Aerospace Engineering, June 1963, pp. 63-65.
5. Cresap, W. L.: Rigid Rotor Development and Flight Tests. Presented at the IAS 30th Annual Meeting, New York, New York, January 22-24, 1962.
6. Cresap, Wesley L., and Lynn, Robert R.: "Research Flight Tests of the High-Performance Iroquois." American Helicopter Society Proceedings of the Nineteenth Annual National Forum, May 1-3, 1963, Washington, D.C., pp. 93-101.
7. Huston, Robert J., and Tapscott, Robert J.: The Results of Some Wind Tunnel and Flight Studies With Helicopters at NASA. Presented at New York Academy of Sciences Conference on Vertical Take-Off and Landing Aircraft, New York, N.Y., December 10-12, 1962.

8. Scheiman, James, and Ludi, LeRoy H.: Qualitative Evaluation of Effect of Helicopter Rotor-Blade Tip Vortex on Blade Airloads. NASA TN D-1637, 1963.
9. Scheiman, James, and Kelley, Henry L.: Comparison of Flight Measured Helicopter Rotor Blade Chordwise Pressure Distributions and Two-Dimensional Airfoil Characteristics. Prepared for Presentation at the CAL-TRECOM Symposium on Dynamic Loads Problems Associated With Helicopters and V/STOL Aircraft, Buffalo, New York, June 26-27, 1963.
10. Sweet, George E., and Jenkins, Julian L., Jr.: Results of Wind-Tunnel Measurements on a Helicopter Rotor Operating at Extreme Thrust Coefficients and High-Tip-Speed Ratios. Presented at the 31st Annual Meeting, Institute of the Aerospace Sciences, New York, N.Y., January 23, 1963.
11. Sanford, T. W., Jr., Hanley, W. J., and De Vore, Gilbert: Height Velocity Diagram Flight Test Project on the Bell 47G3B Helicopter. Presented at the 19th Annual National Forum of American Helicopter Society, May 1-3, 1963, Washington, D.C.
12. Sweet, George E., and Jenkins, Julian L., Jr.: Wind-Tunnel Investigation of the Drag and Static Stability Characteristics of Four Helicopter Fuselage Models. NASA TN D-1363, 1962.
13. Jenkins, Julian L., Jr., Winston, Matthew M., and Sweet, George E.: A Wind-Tunnel Investigation of the Longitudinal Aerodynamic Characteristics of Two Full-Scale Helicopter Fuselage Models With Appendages. NASA TN D-1364, 1962.
14. Biggers, James C., McCloud, John L. III, and Patterakis, Pete: Wind-Tunnel Tests of Two Full-Scale Helicopter Fuselages. NASA TN D-1548, 1962.
15. Carpenter, Paul J.: "Future Performance of Rotary-Wing Aircraft." Astronautics and Aerospace Engineering, June 1963, pp. 60-62.

16. McCloud, John L. III, Biggers, James C., and Maki, Ralph L.: Full-Scale Wind-Tunnel Tests of a Medium-Weight Utility Helicopter at Forward Speeds. NASA TN D-1887, 1963.
17. Spreemann, Kenneth P.: Investigation of a Semispan Tilting Propeller Configuration and Effects of Ratio of Wing Chord to Propeller Diameter on Several Small-Chord Tilting-Wing Configurations at Transition Speeds. NASA TN D-1815, 1963.
18. Pegg, Robert J.: Summary of Flight-Test Results of the VZ-2 Tilt-Wing Aircraft. NASA TN D-989, 1962.
19. Pegg, Robert J.: Flight-Test Investigation of Ailerons as a Source of Yaw Control on the VZ-2 Tilt-Wing Aircraft. NASA TN D-1375, 1962.
20. Holzhauser, Curt A., and Deckert, Wallace H.: Low-Speed Operation of Propeller-Driven STOL Aircraft. Presented at DOD Symposium on V/STOL Aircraft, Kirtland Air Force Base, New Mexico, April 23-24, 1963.
21. McKinney, M. O., Kirby, R. H., and Newsom, W. A.: Aerodynamic Factors to be Considered in the Design of Tilt-Wing V/STOL Airplanes. Presentation at the New York Academy of Sciences Conference on VTOL Aircraft, New York, New York, December 10-12, 1962.
22. Quigley, Hervey C., and Lawson, Herbert F., Jr.: Simulator Study of the Lateral-Directional Handling Qualities of a Large Four-Propellered STOL Transport Airplane. NASA TN D-1773, 1963.
23. Newsom, William A., Jr.: Force-Test Investigation of the Stability and Control Characteristics of a Four-Propeller Tilt-Wing VTOL Model With a Programmed Flap. NASA TN D-1389, 1962.

24. Newsom, William A., Jr.: Flight Investigation of the Longitudinal Stability and Control Characteristics of a Four-Propeller Tilt-Wing VTOL Model With a Programed Flap. NASA TN D-1390, 1962.
25. Winston, Matthew M., and Huston, Robert J.: Propeller Slipstream Effects as Determined From Wing Pressure Distribution on a Large-Scale Six-Propeller VTOL Model at Static Thrust. NASA TN D-1509, 1962.
26. Huston, Robert J., Ward, John F., and Winston, Matthew M.: Wing and Flap Loads Obtained From a Wind-Tunnel Investigation of a Large-Scale V/STOL Model. NASA TN D-1634, 1963.
27. Yaggy, Paul F., and Mort, Kenneth W.: Wind-Tunnel Tests of Two VTOL Propellers in Descent. NASA TN D-1766, 1963.
28. Turner, Howard L., and Drinkwater, Fred J. III: Longitudinal Trim Characteristics of a Deflected Slipstream V/STOL Aircraft During Level Flight at Transition Flight Speeds. NASA TN D-1430, 1962.
29. McKinney, M. O.: Propeller V/STOL Aircraft. Presented at DOD Symposium on V/STOL Aircraft, Kirtland Air Force Base, New Mexico, April 23-24, 1963.
30. Newsom, William A., Jr., and Tosti, Louis P.: Slipstream Flow Around Several Tilt-Wing VTOL Aircraft Models Operating Near the Ground. NASA TN D-1382, 1962.
31. O'Bryan, Thomas C.: An Experimental Study of the Effect of Downwash From a Twin-Propeller VTOL Aircraft on Several Types of Ground Surfaces. NASA TN D-1239, 1962.
32. Reed, Wilmer H. III, and Bennett, Robert M.: Propeller Whirl Considerations for V/STOL Aircraft. Presentation at the CAL-TRECOM Symposium on Dynamic Loads Problems Associated With Helicopters and V/STOL Aircraft, Buffalo, New York, June 26-27, 1963.

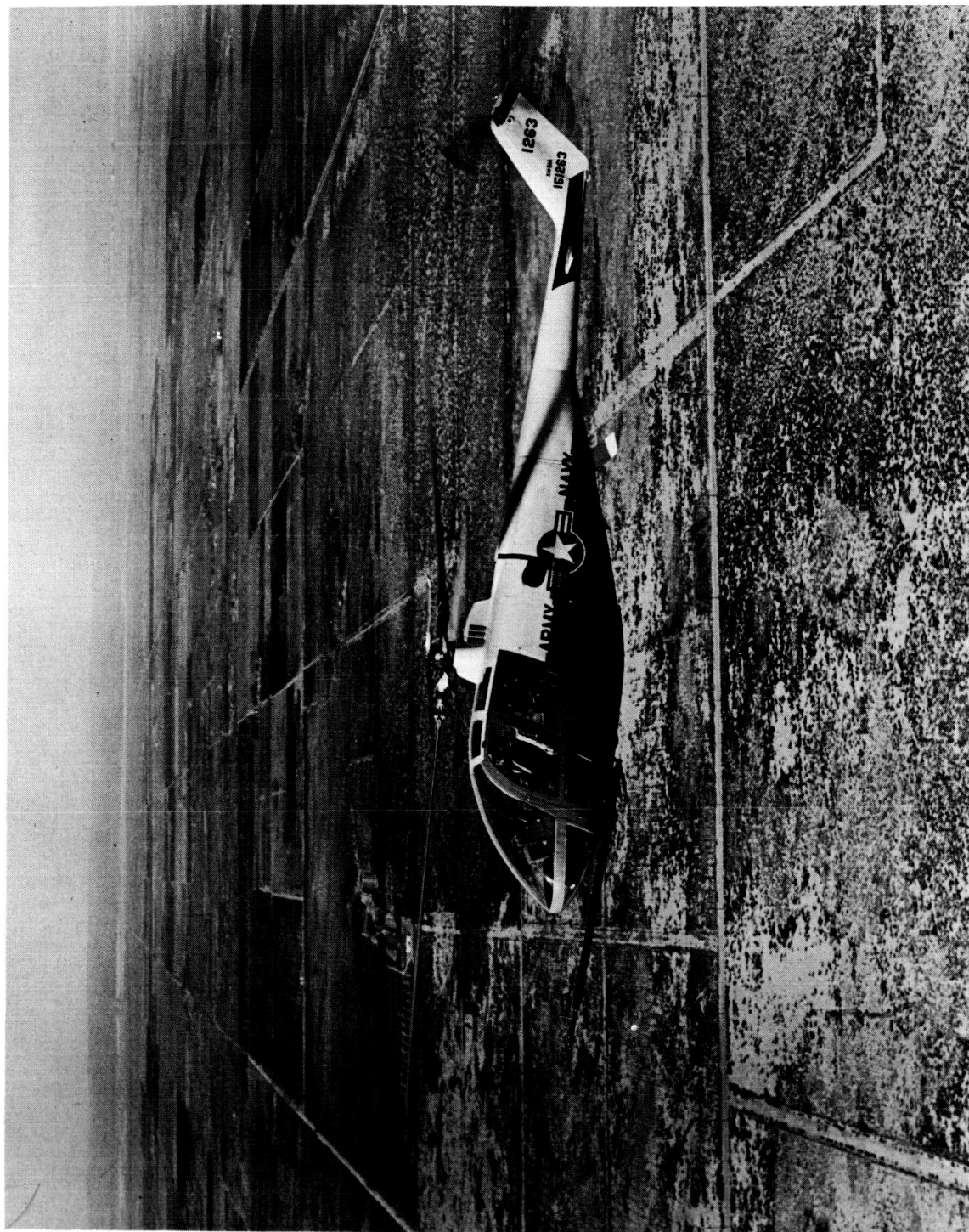
33. Aoyagi, Kiyoshi, Hickey, David H., and deSavigny, Richard A.: Aerodynamic Characteristics of a Large-Scale Model With a High Disk-Loading Lifting Fan Mounted in the Fuselage. NASA TN D-775, 1961.
34. Maki, Ralph L., and Hickey, David H.: Aerodynamics of a Fan-in-Fuselage Model. NASA TN D-789, 1961.
35. Goldsmith, Robert H., and Hickey, David H.: Characteristics of Aircraft With Lifting-Fan Propulsion Systems for V/STOL. IAS Paper 63-27, Presented at IAS Annual Meeting, January 21-23, 1963.
36. Hickey, David H., and Kelly, Mark W.: Characteristics of V/STOL Aircraft With High Disk-Loading Fans. Presented at DOD Symposium on V/STOL Aircraft, Kirtland Air Force Base, New Mexico, April 23-24, 1963.
37. deSavigny, Richard A., and Hickey, David H.: Aerodynamic Characteristics in Ground Effect of a Large-Scale Model With a High Disk-Loading Lifting Fan Mounted in the Fuselage. NASA TN D-1557, 1963.
38. Hickey, David H., and Hall, Leo P.: Aerodynamic Characteristics of a Large-Scale Model With Two High Disk-Loading Fans Mounted in the Wing. NASA TN D-1650, 1963.
39. Starkey, H. B., and True, H. C.: "Design and Development of the Army XV-5A Lift Fan Powered V/STOL Aircraft." American Helicopter Society Proceedings of the Nineteenth Annual National Forum, May 1-3, 1963, Washington, D.C., pp. 102-110.
40. James, Harry A., and Sanders, Karl L.: "Fan-in-Wing V/STOL Aircraft." Astronautics and Aerospace Engineering, June 1963, pp. 66-71.
41. Campbell, John P.: Ground Proximity Effects Associated With V/STOL Aircraft. Reprint From Eighth Anglo-American Aeronautical Conference, 1961.

42. Kelley, Henry L.: Transition and Hovering Flight Characteristics of a Tilt-Duct VTOL Research Aircraft. NASA TN D-1491, 1962.
43. McKinney, M. O., and Newsom, W. A.: Experimental Research on 4-Duct Tandem VTOL Aircraft Configurations. Presented to the Eighteenth Annual Forum of the American Helicopter Society, Washington, D.C., May 3-5, 1962.
44. Paxhia, V. B., and Sing, E. Y.: Design Development of a Dual Tandem Ducted Propeller VTOL Aircraft. IAS Paper No. 63-30, Presented at the IAS 31st Annual Meeting, New York, New York, January 21-23, 1963.
45. Newsom, William A., Jr.: Aerodynamic Characteristics of Four-Duct Tandem VTOL-Aircraft Configurations. NASA TN D-1481, 1963.
46. Yaggy, Paul F., and Mort, Kenneth W.: A Wind-Tunnel Investigation of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D-776, 1961.
47. Yaggy, Paul F., and Goodson, Kenneth W.: Aerodynamics of a Tilting Ducted Fan Configuration. NASA TN D-785, 1961.
48. Goodson, Kenneth W., and Grunwald, Kalman J.: Aerodynamic Characteristics of a Powered Semispan Tilting-Shrouded-Propeller VTOL Model in Hovering and Transition Flight. NASA TN D-981, 1961.
49. Grunwald, Kalman J., and Goodson, Kenneth W.: Aerodynamic Loads on an Isolated Shrouded-Propeller Configuration for Angles of Attack From -10° to 110° . NASA TN D-995, 1961.
50. Mort, Kenneth W., and Yaggy, Paul F.: Aerodynamic Characteristics of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D-1301, 1962.
51. Kuhn, Richard E., Reeder, John P., and Alford, William J., Jr.: "Jet V/STOL Tactical Aircraft." Astronautics and Aerospace Engineering,

52. Gibson, E. B.: "The Hummingbird Program." American Helicopter Society Proceedings of the Nineteenth Annual National Forum, May 1-3, 1963, Washington, D.C., pp. 111-118.
53. Spreemann, Kenneth P.: Induced Interference Effects on Jet and Buried-Fan VTOL Configurations in Transition. NASA TN D-731, 1961.
54. Spreemann, Kenneth P.: Investigation of Interference of a Deflected Jet With Free Stream and Ground on Aerodynamic Characteristics of a Semispan, Delta-Wing VTOL Model. NASA TN D-915, 1961.
55. Otis, James H., Jr.: Induced Interference Effects on a Four-Jet VTOL Configuration With Various Wing Planforms in the Transition Speed Range. NASA TN D-1400, 1962.
56. Vogler, Raymond D.: Surface Pressure Distributions Induced on a Flat Plate by a Cold Air Jet Issuing Perpendicularly From the Plate and Normal to a Low-Speed Free-Stream Flow. NASA TN D-1629, 1963.
57. Anderson, Seth B., and Tapscott, Robert J.: A Review of V/STOL Handling Qualities Criteria. Presented at the DOD Symposium on V/STOL Aircraft, Kirtland Air Force Base, New Mexico, April 23-24, 1963.
58. Rolls, L. Stewart, and Drinkwater, Fred J. III: A Flight Determination of the Attitude Control Power and Damping Requirements for a Visual Hovering Task in the Variable Stability and Control X-14A Research Vehicle. NASA TN D-1328, 1962.
59. Gerdes, Ronald M., and Weick, Richard F.: A Preliminary Piloted Simulator and Flight Study of Height Control Requirements for V/STOL Aircraft. NASA TN D-1201, 1962.

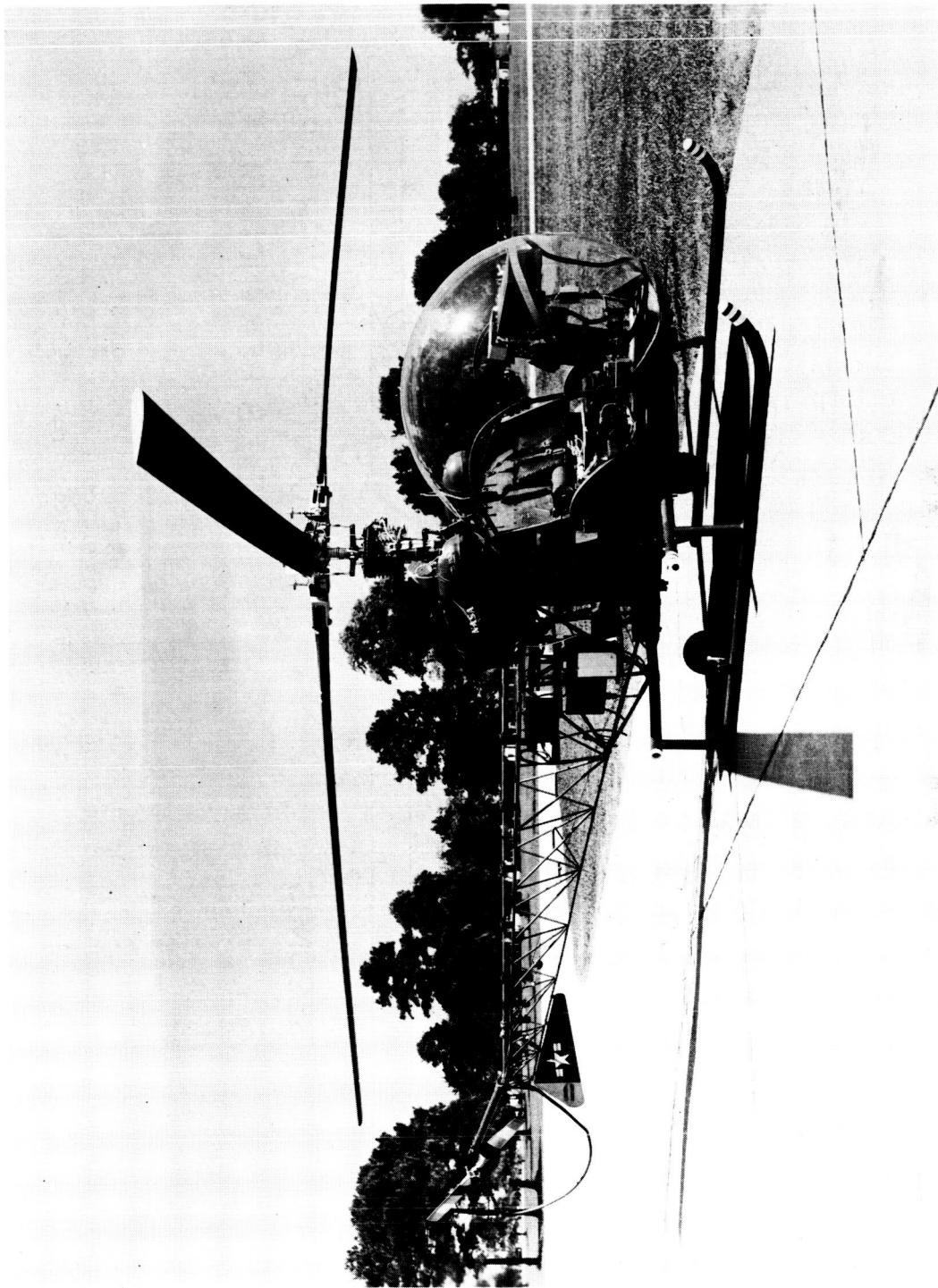
60. Garren, John F., Jr., and Assadourian, Arthur: VTOL Height-Control Requirements in Hovering as Determined From Motion Simulator Study. NASA TN D-1488, 1962.
61. AGARD Report 408: Recommendations for V/STOL Handling Qualities. October 1962.
62. Anderson, Seth B.: An Examination of Handling-Qualities Criteria for V/STOL Aircraft. NASA TN D-331, 1960.
63. Goldberg, Joseph H., and Gangwish, Robert C.: Required Lateral Handling Qualities for Helicopters in Low-Speed Instrument Flight. Princeton University Aero. Eng. Dep., Princeton, N.J., Report No. 496, February 1960.
64. Seckel, E., Traybar, J. J., and Miller, G. E.: Longitudinal Handling Qualities for Hovering. Department of Aeronautical Engineering, Princeton University, Report No. 594, December 1961.
65. A'Harrah, R. C., and Kwiatkowski, S. F.: "A New Look at V/STOL Flying Qualities." Aerospace Engineering, Volume 20, July 1961, pp. 22-23, 86-92.
66. Seckel, E., Traybar, J. J., and Miller, G. E.: A Note on the Effect of Helicopter Dynamics on Steep Instrument Approaches. Princeton University Aero. Eng. Dept., Princeton, New Jersey. Report No. 600, February 1962.
67. Trant, James P., Jr., and Algranti, Joseph S.: Investigation of VTOL Approach Methods by Use of Ground-Controlled-Approach Procedures. NASA TN D-1489, 1962.
68. Quigley, Hervey C., and Innis, Robert C.: Handling Qualities and Operational Problems of a Large Four-Propeller STOL Transport Airplane. NASA TN D-1647, 1963.

69. Reeder, John P.: Operational Aspects of V/STOL Aircraft. Presented at the DOD Symposium on V/STOL Aircraft, Kirtland Air Force Base, New Mexico, April 23-24, 1963.
70. Collar, Thomas E.: A Rationale for the Determination of Certain VTOL Handling Qualities Criteria. Paper Presented to AGARD Flight Mechanics Panel, Athens, Greece, July 8-10, 1963.



NASA

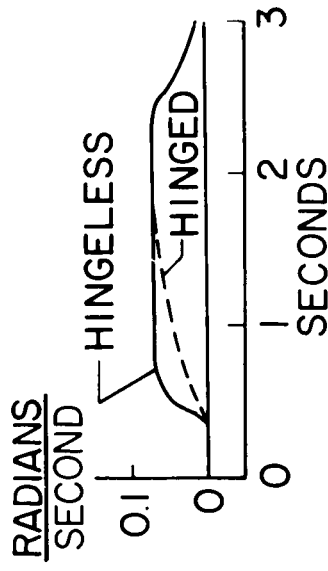
Figure 1.- Lockheed XH-51A hingeless-rotor helicopter.



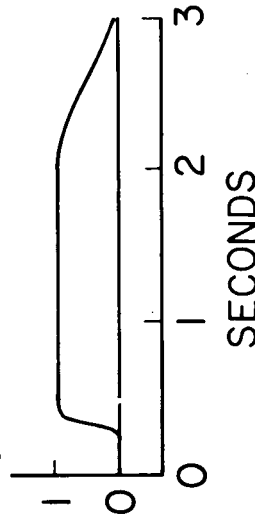
NASA

Figure 2.- NASA research helicopter with Bell hingeless rotor installed.

PITCHING VELOCITY,

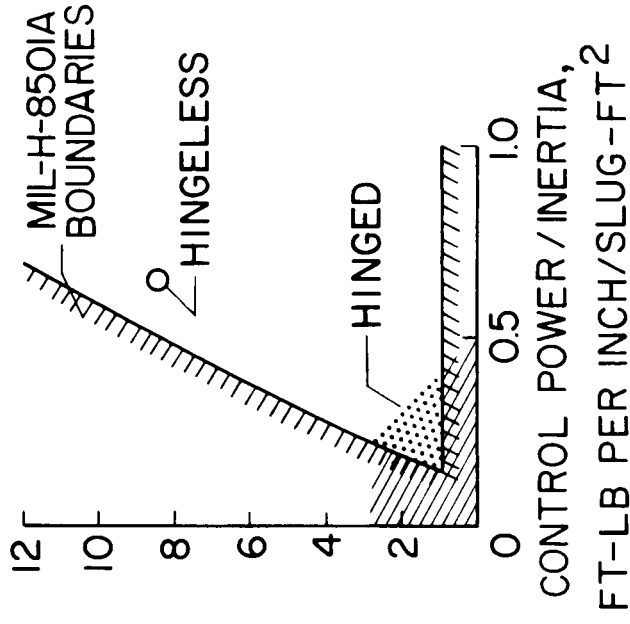


DEFLECTION FROM TRIM, INCHES



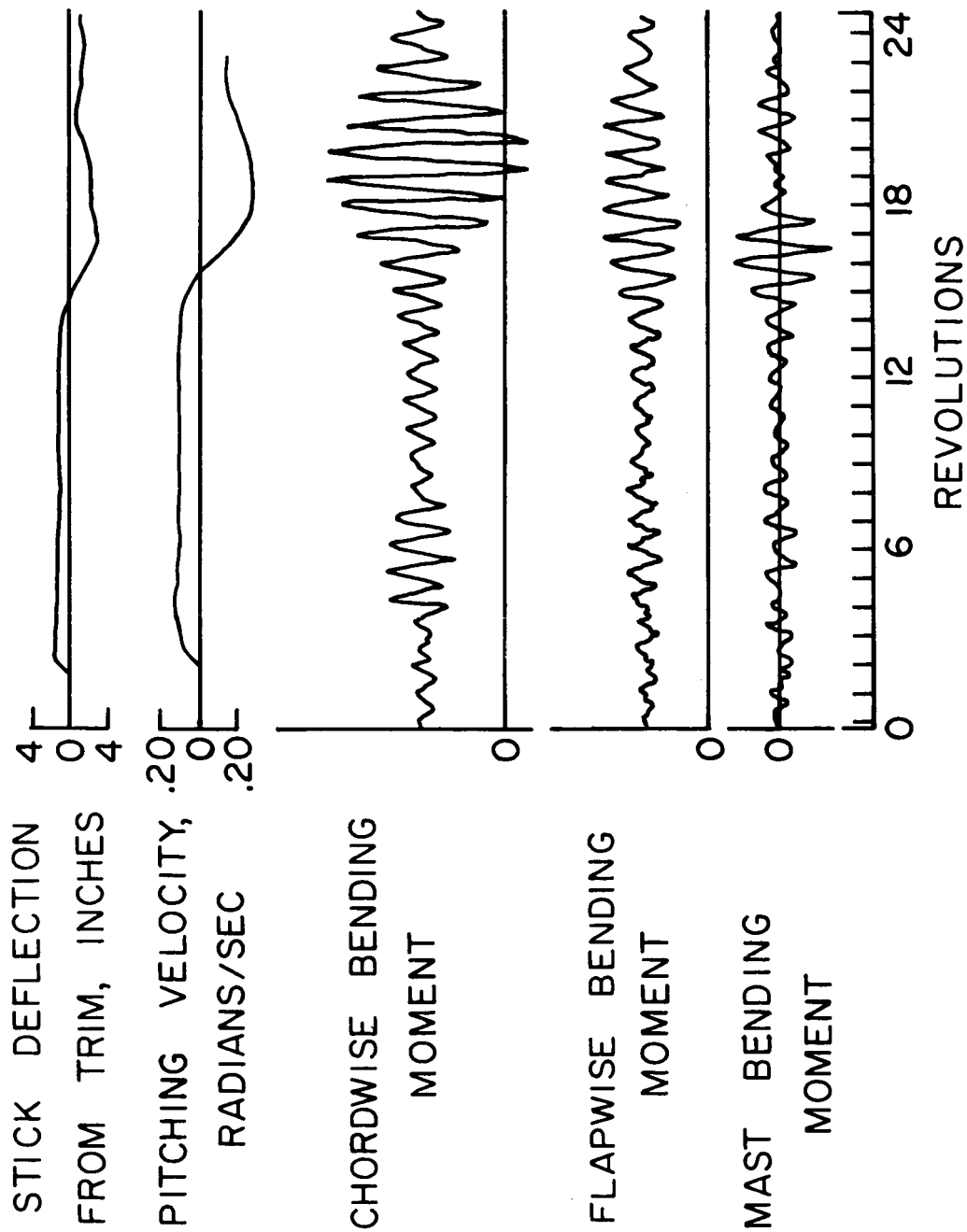
DAMPING / INERTIA,

$\frac{\text{FT-LB PER RAD/SEC}}{\text{SLUG-FT}^2}$



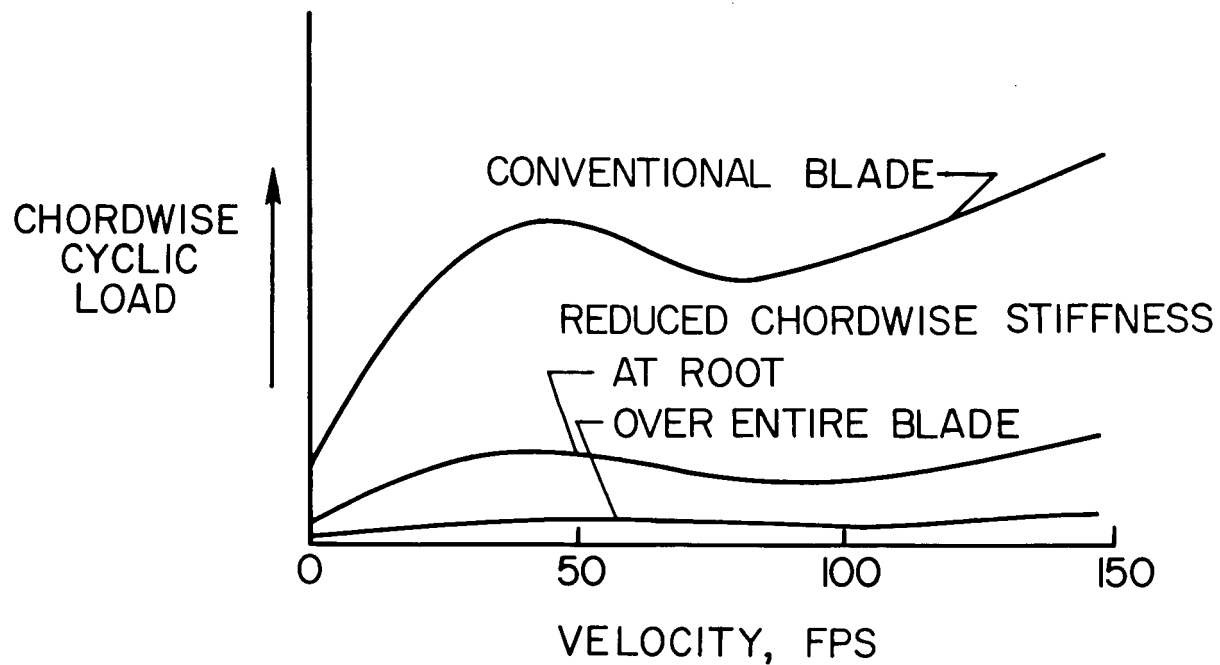
NASA

Figure 3.- Control-response and handling-qualities comparison of hingeless-rotor helicopter and conventional hinged-rotor helicopter in hovering flight. (Figure taken from reference 7.)



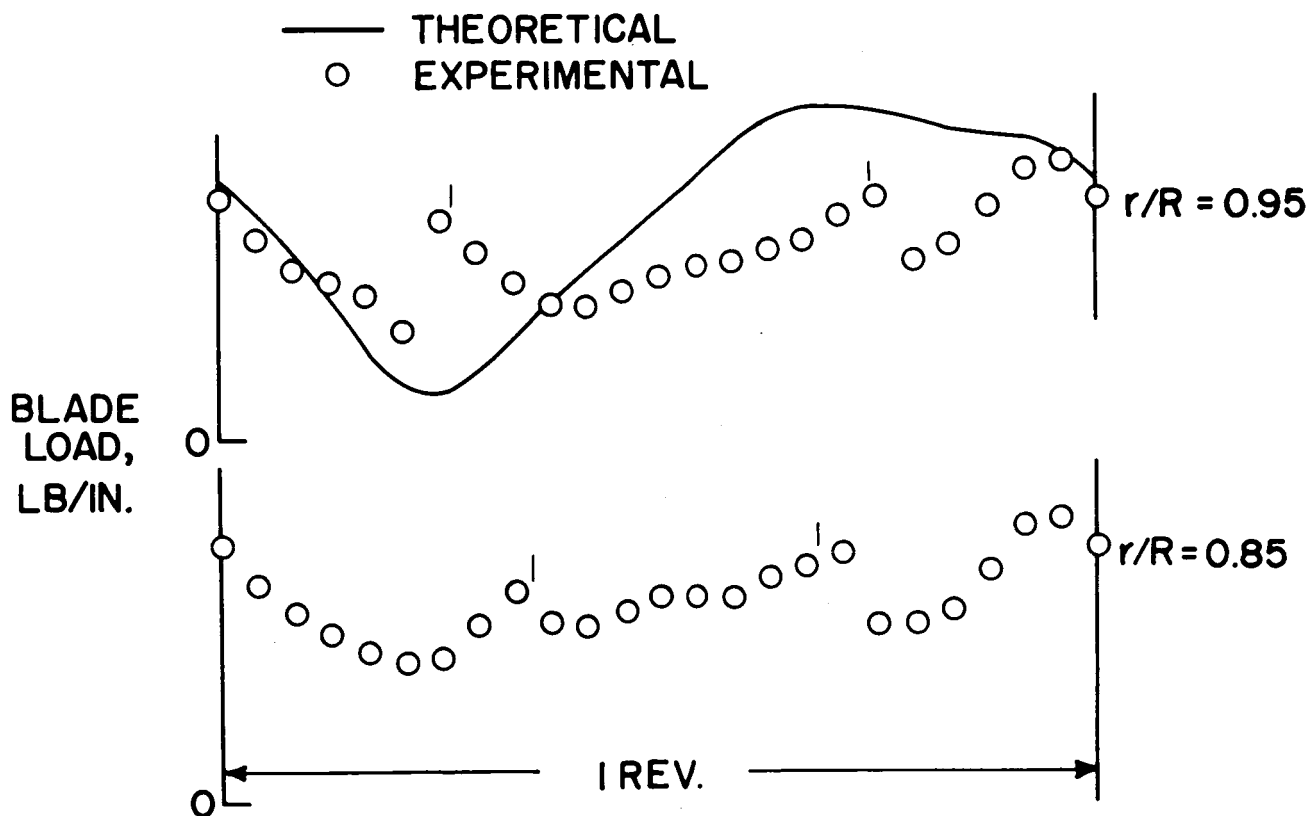
NASA

Figure 4.- Structural-loads time history during longitudinal maneuver and recovery with hingeless-rotor helicopter in hovering flight. (Figure taken from reference 7.)



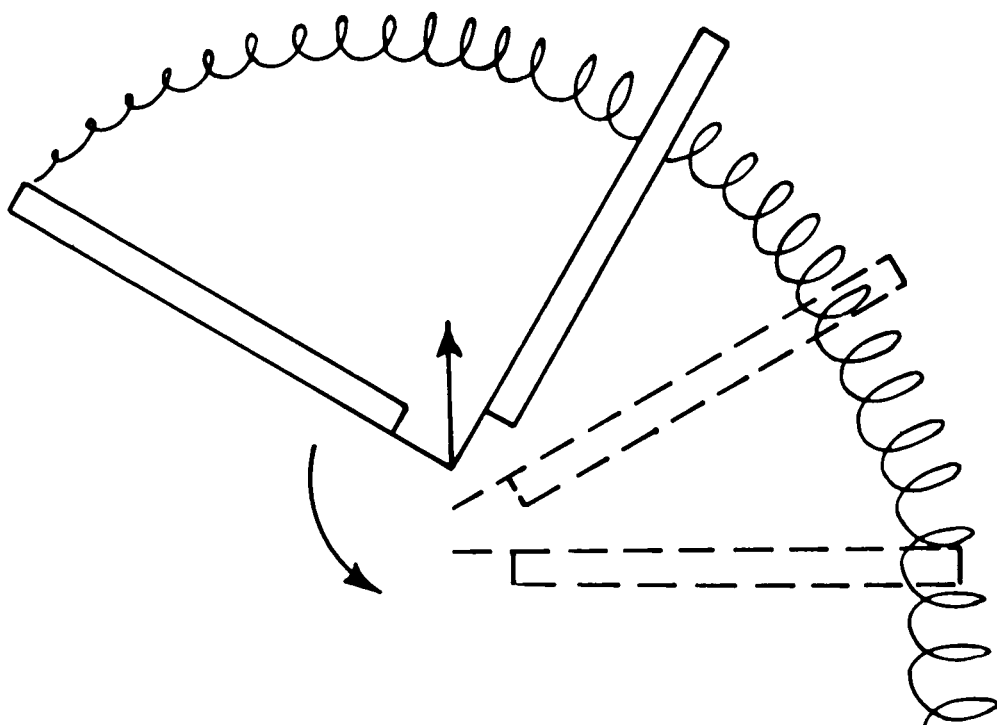
NASA

Figure 5.- Hingeless-rotor wind-tunnel data showing effect of blade chordwise stiffness on chordwise cyclic blade loads.



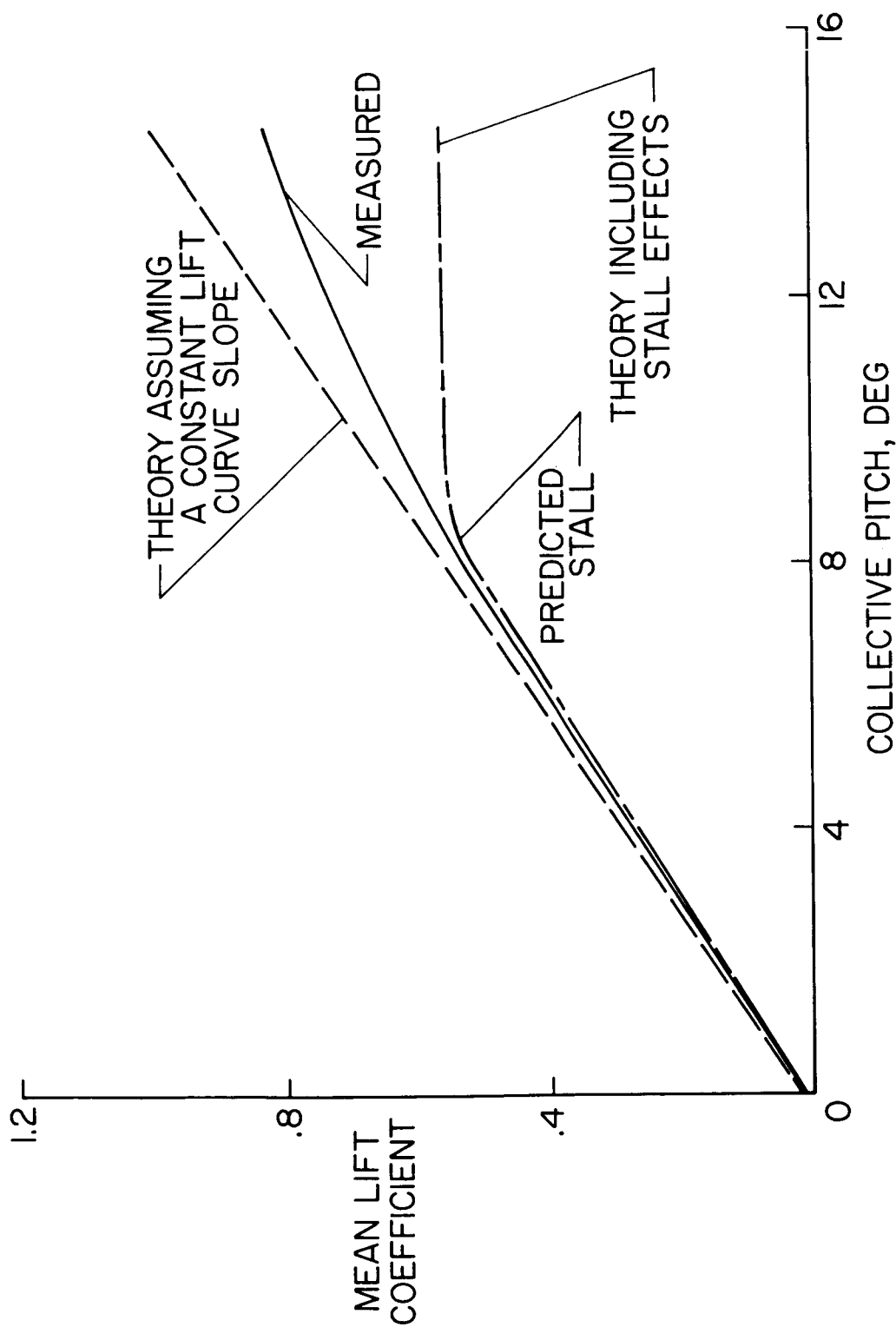
NASA

Figure 6.- Comparison of experimental and theoretical blade loads for a single-rotor helicopter in forward flight. (Figure taken from reference 1.)



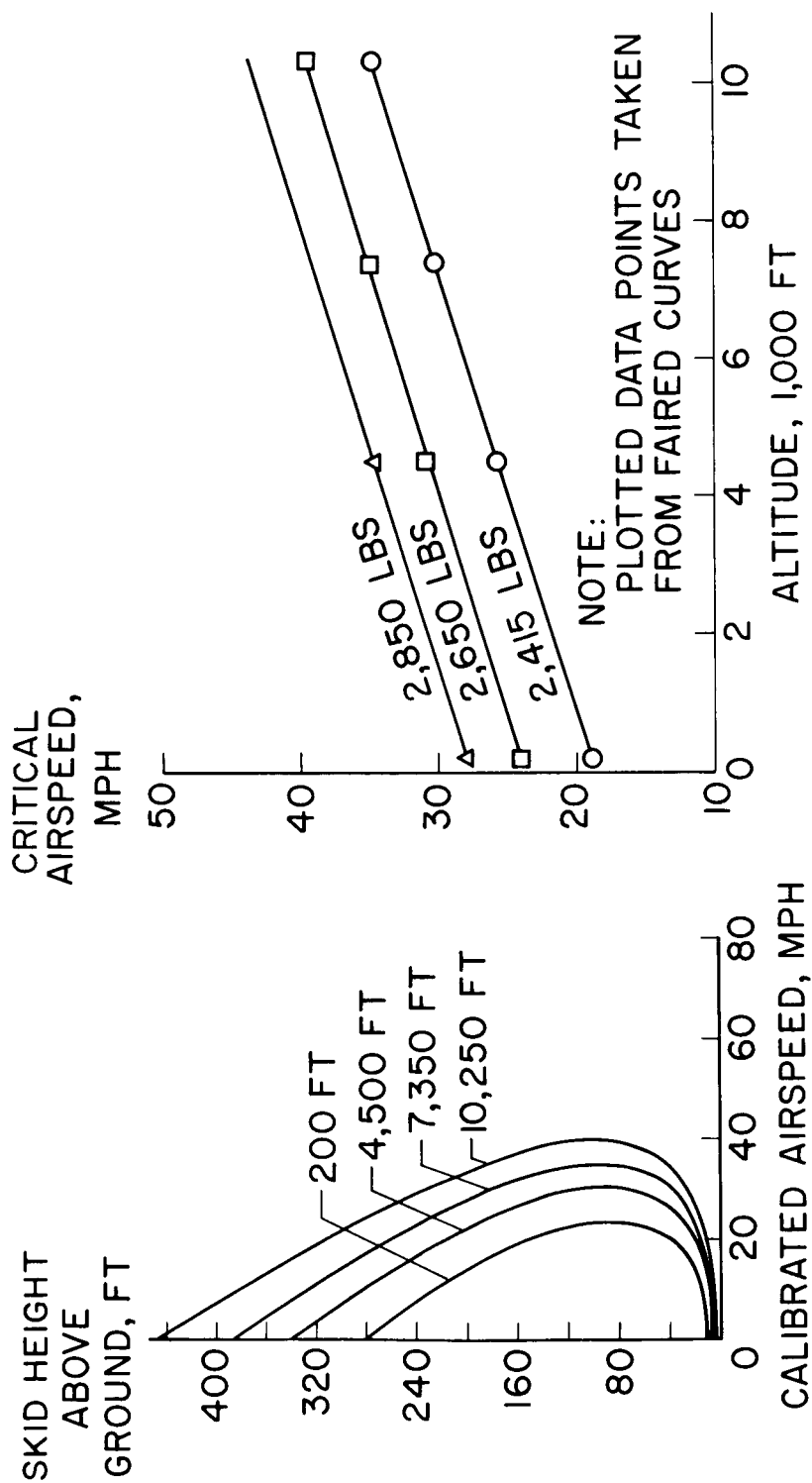
NASA

Figure 7.- Sketch illustrating manner in which tip vortex from one blade is hit by next blade. (Figure taken from reference 1.)



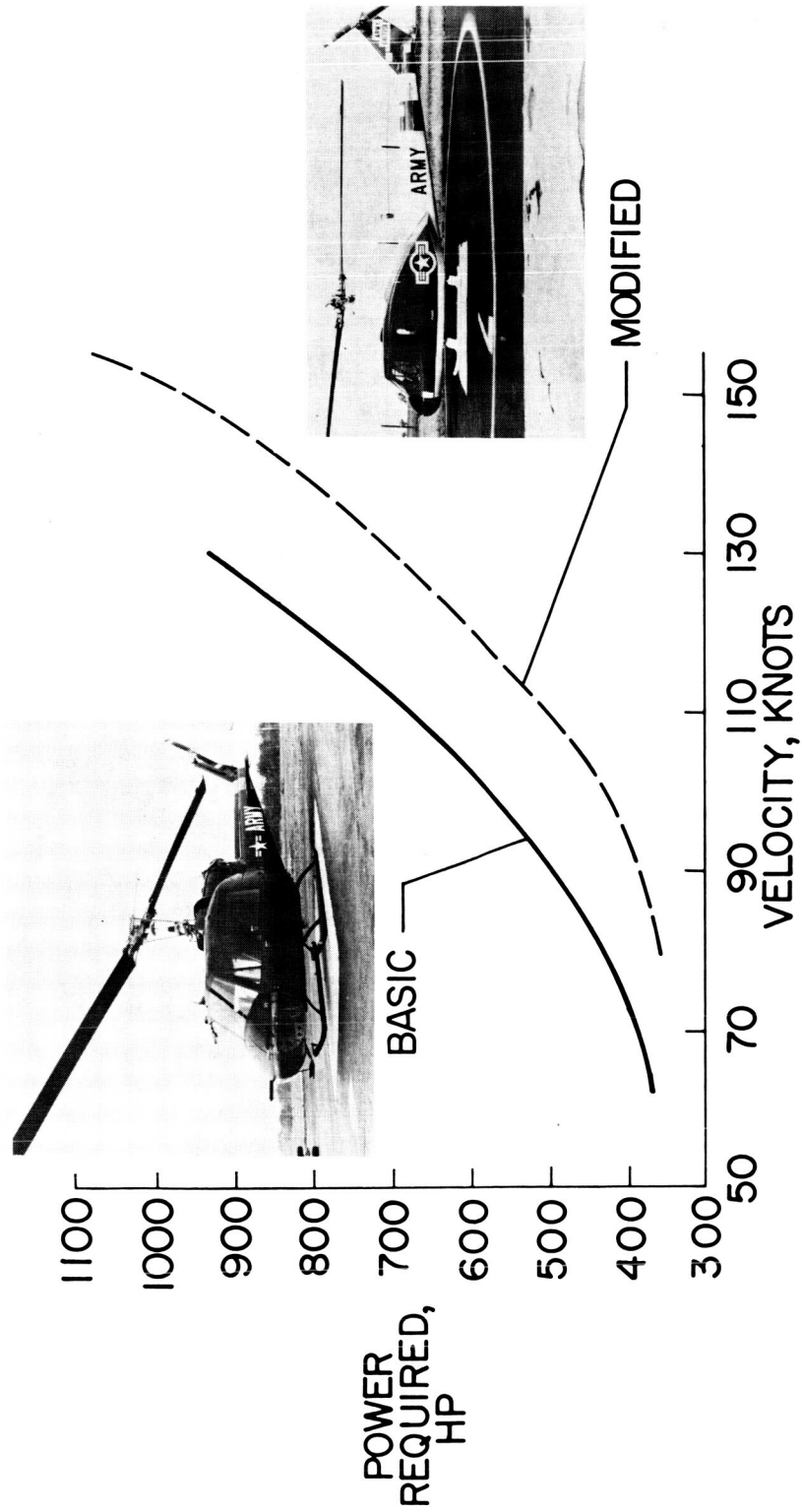
NASA

Figure 8.- Comparison of rotor thrust (in terms of hovering mean lift coefficient) with simple and refined theory. (Figure taken from reference 10.)



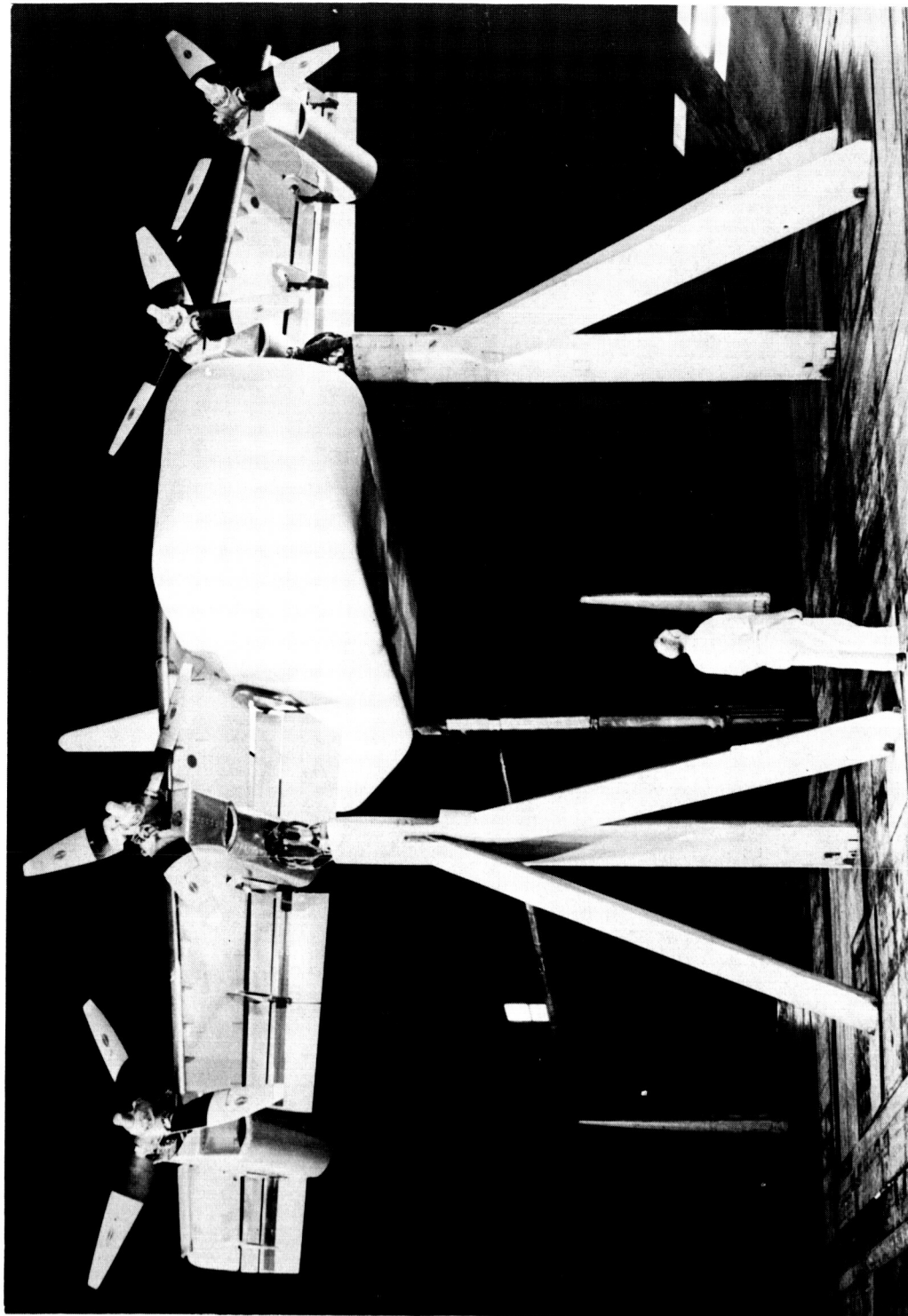
NASA

Figure 9.- Helicopter height-velocity diagram data obtained in FAA flight investigation. (Data from reference 11.)



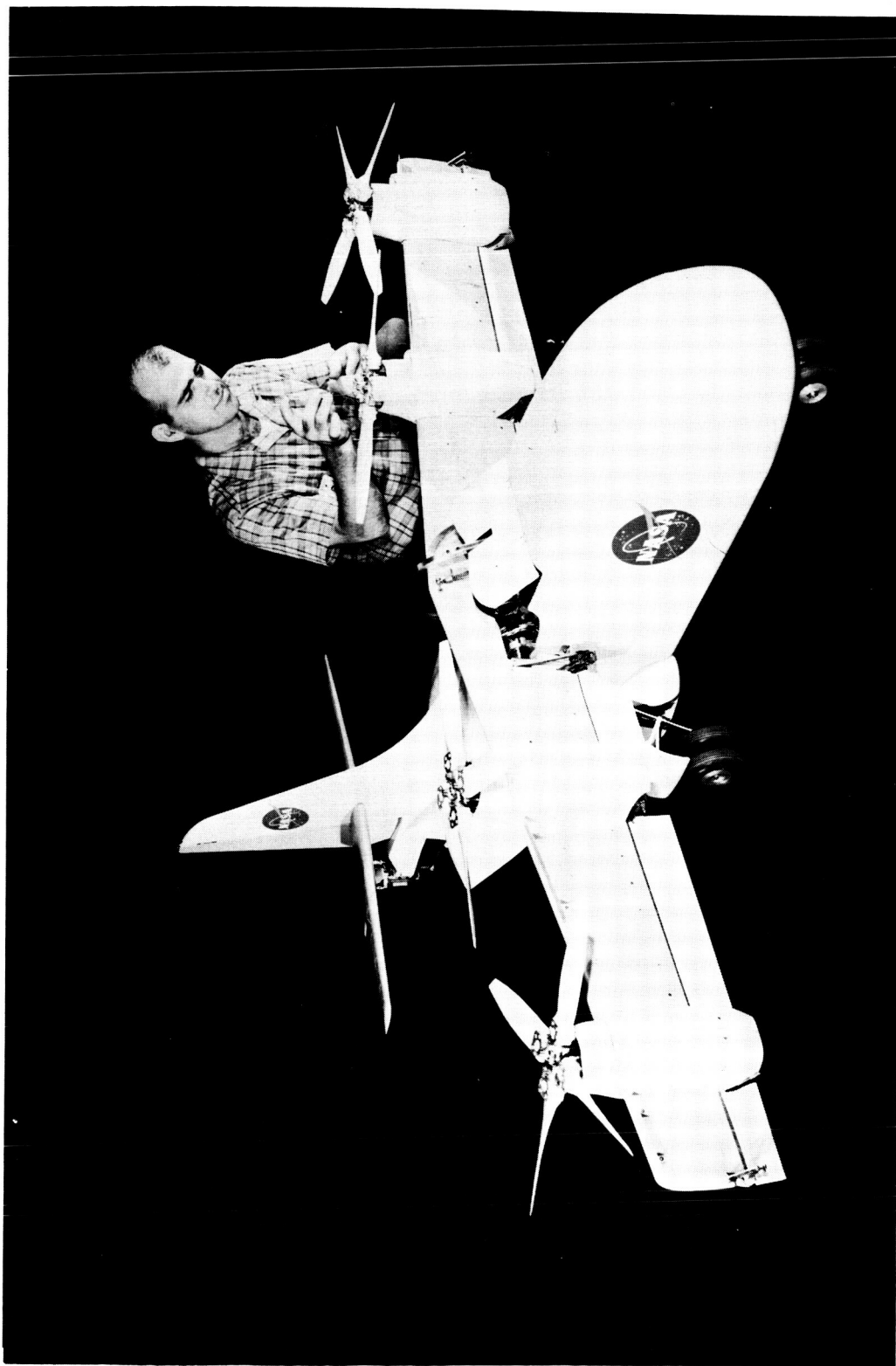
NASA

Figure 10.- Effect of drag cleanup on performance of UH-1B helicopter.
(Figure taken from reference 15.)



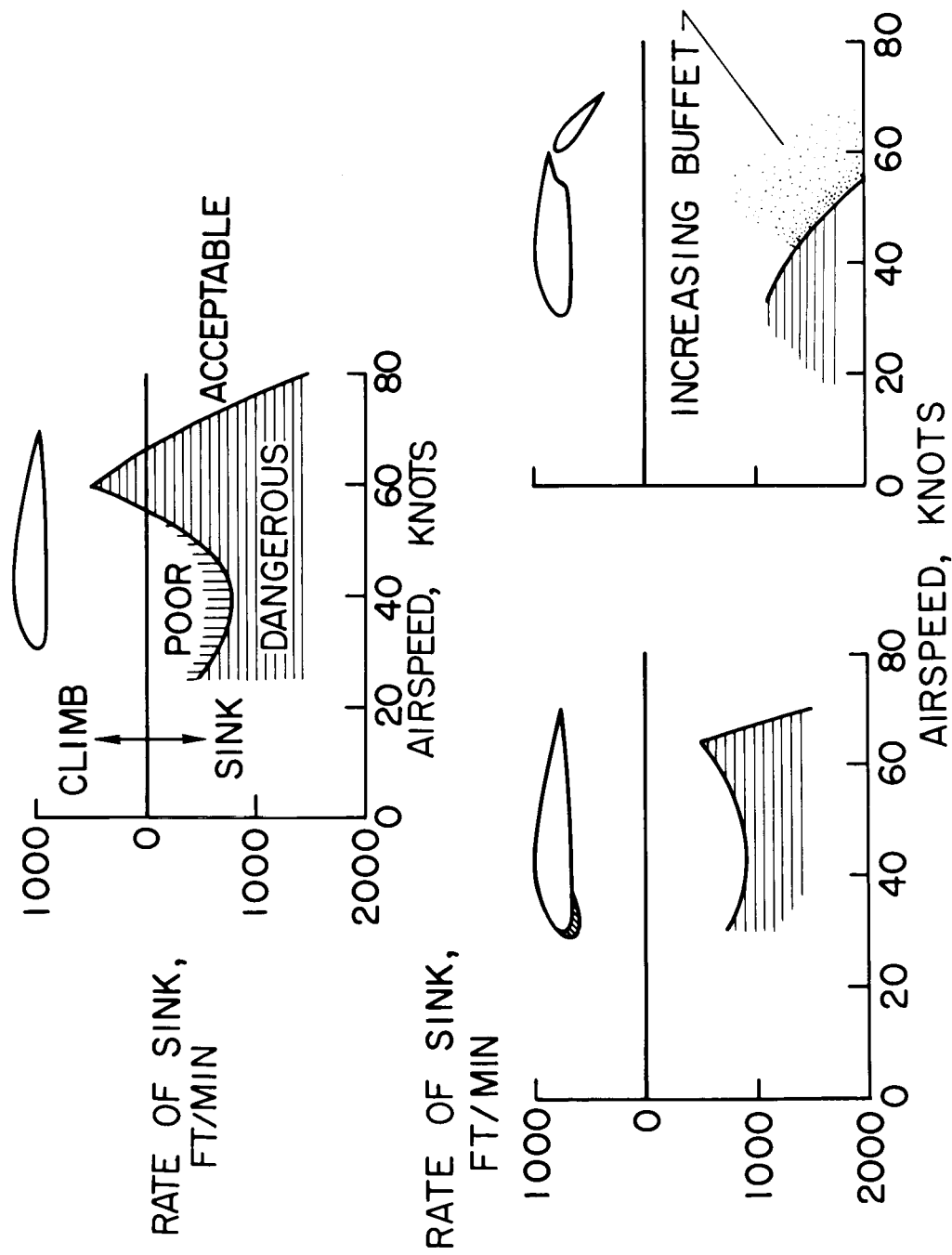
NASA

Figure 11.- Large-scale model of XC-142 Tri-Service VTOL airplane in NASA Ames Research Center 40- by 80-foot wind tunnel.



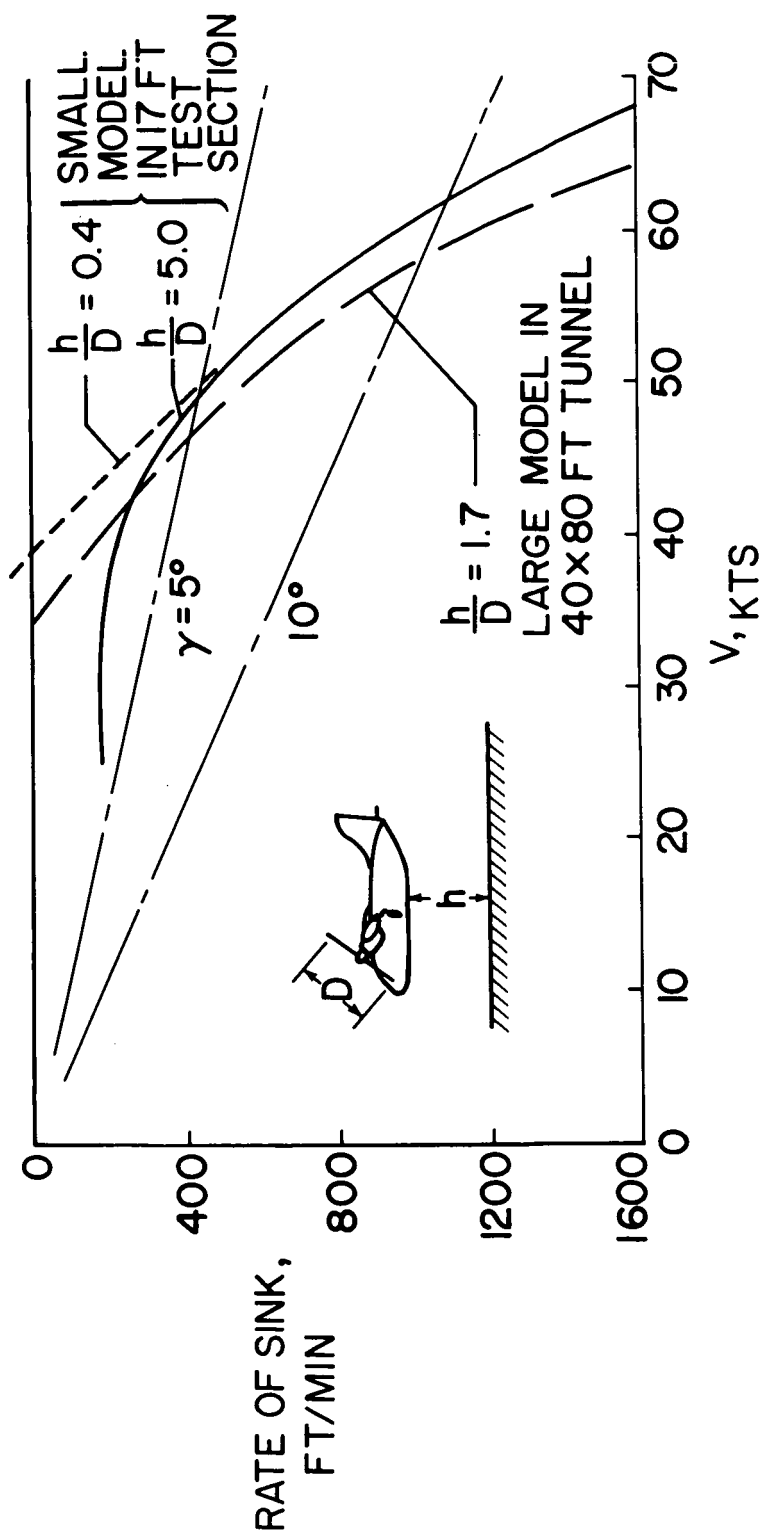
NASA

Figure 12.- Free-flying model of XC-142 airplane used in dynamic stability and control research at the NASA Langley Research Center.



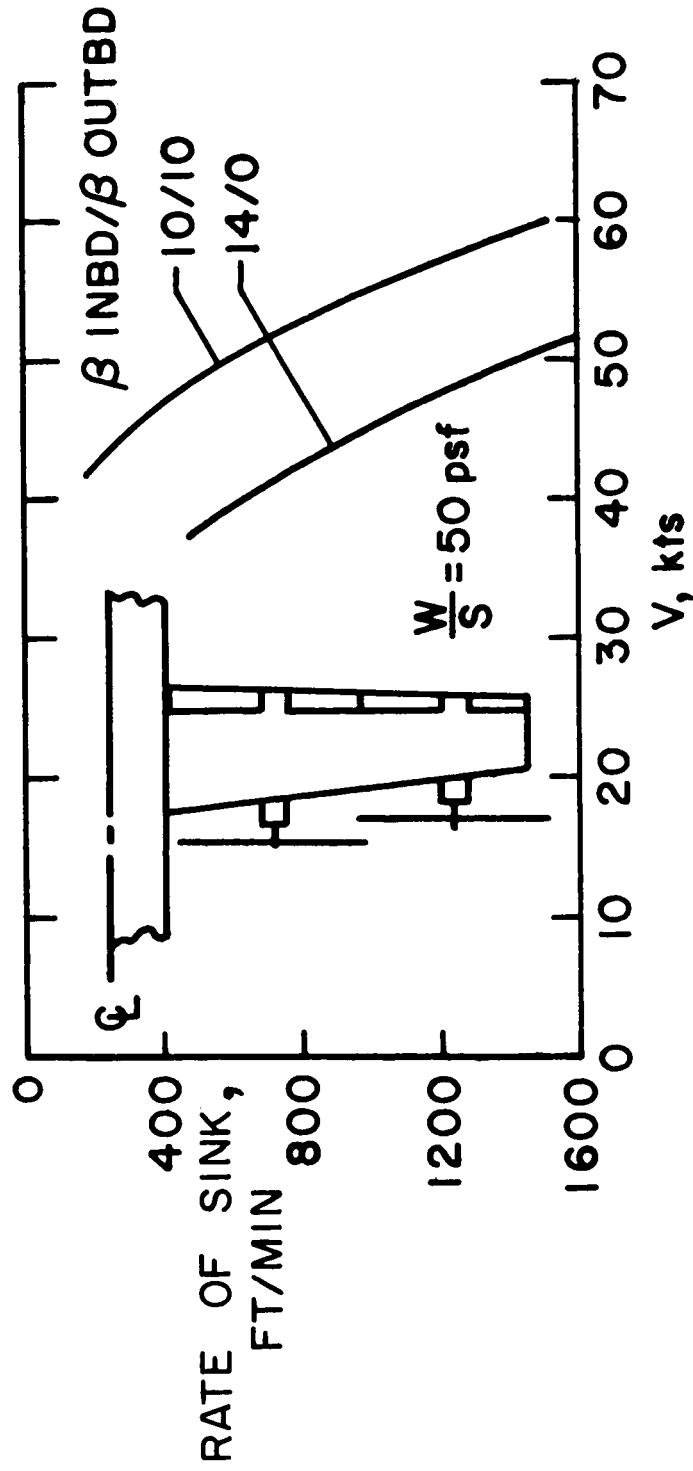
NASA

Figure 13.- Effect of leading-edge droop and trailing-edge flaps on flying qualities of VZ-2 research airplane in transition.



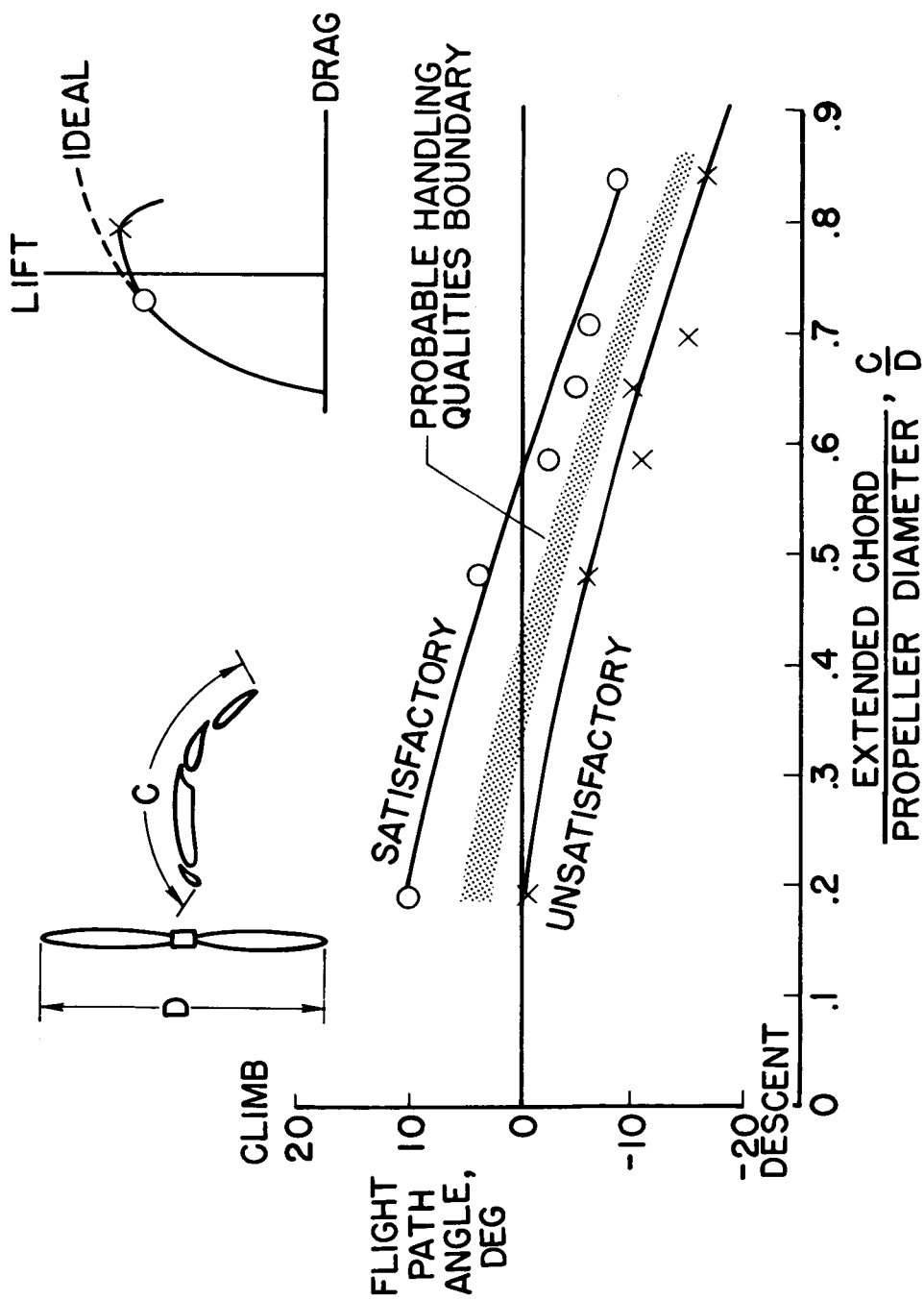
NASA

Figure 14.- Effect of ground proximity on wing-stall boundaries for a tilt-wing V/STOL airplane configuration.



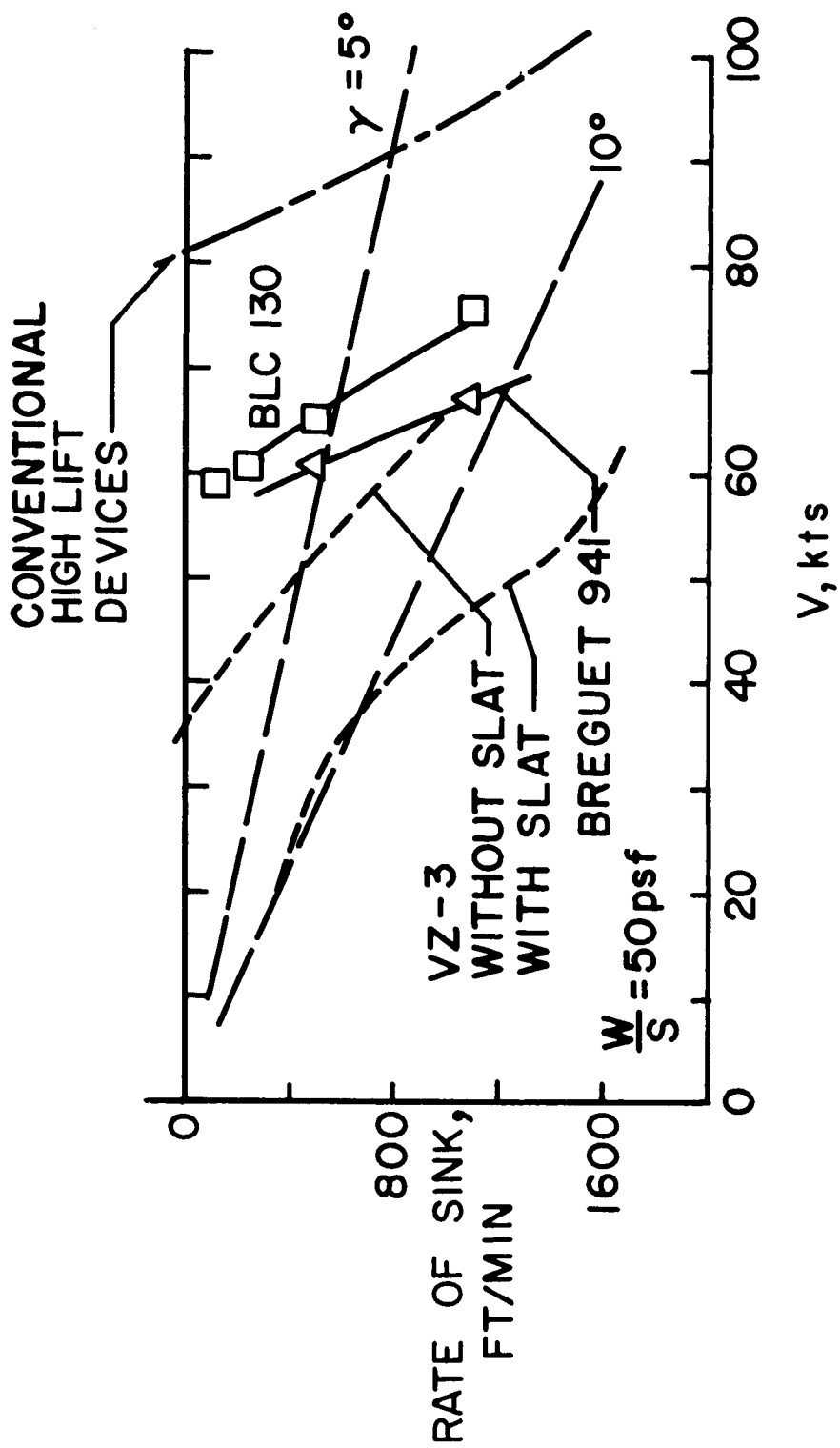
NASA

Figure 15.- Effect of differential blade pitch between inboard and outboard propellers on stall speed of a four-propeller configuration with large-chord double-slotted flaps. (Figure taken from reference 20.)



NASA

Figure 16.- Effect of chord-diameter ratio on permissible angle of descent for satisfactory handling qualities. (Figure taken from reference 21.)

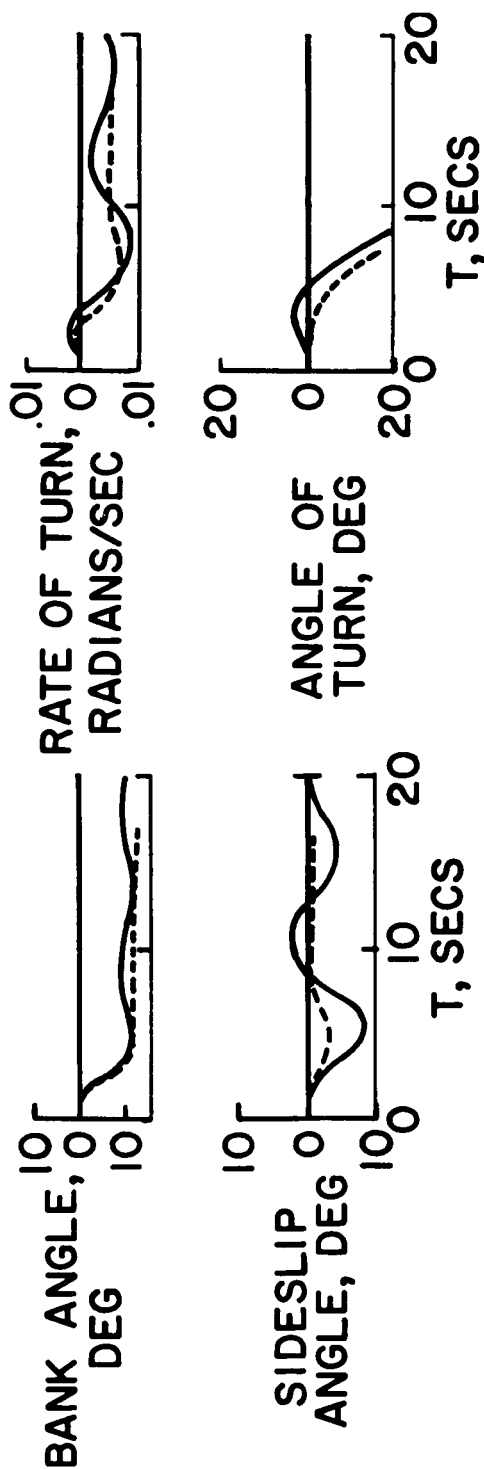


NASA

Figure 17.- Landing-approach speeds chosen by pilots of STOL aircraft.
(Figure taken from reference 20.)

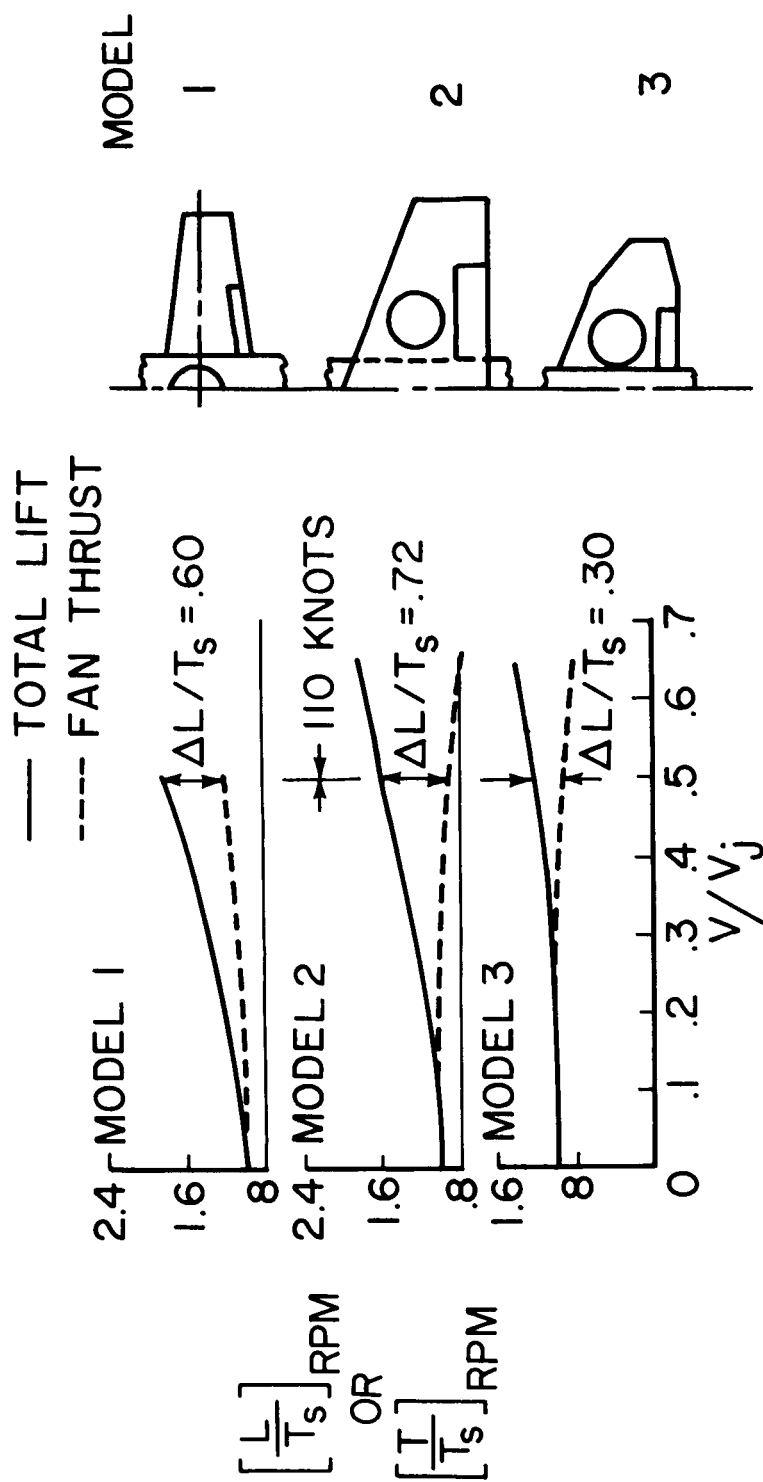
— BLC-130

----- STABILITY AUGMENTED (SIMULATOR)



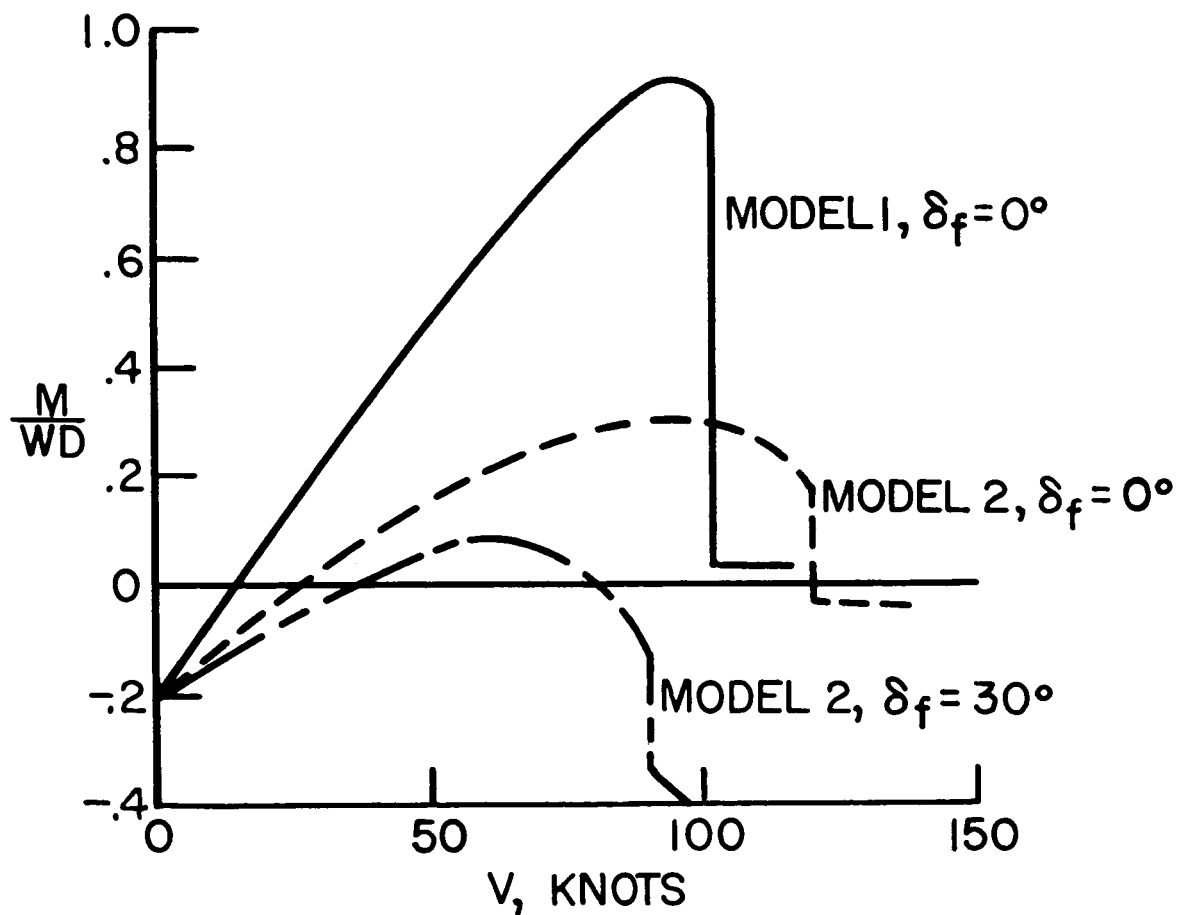
NASA

Figure 18.- Effect of stability augmentation (increased directional stability $C_{n\beta}$ and sideslipping acceleration damping $C_{n\dot{\beta}}$) on lateral controllability of BLC-130. (Figure taken from reference 20.)



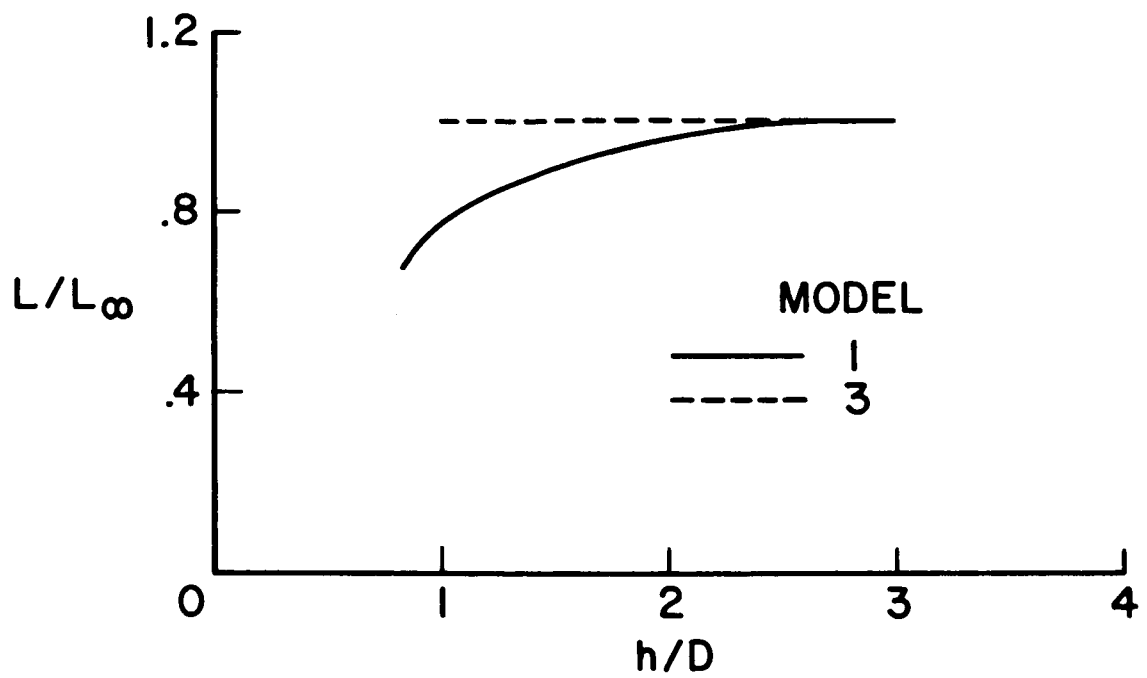
NASA

Figure 19.- Variation of lift and thrust with velocity ratio for three ducted-fan configurations. $\alpha = 0^\circ$. (Figure taken from reference 35.)



NASA

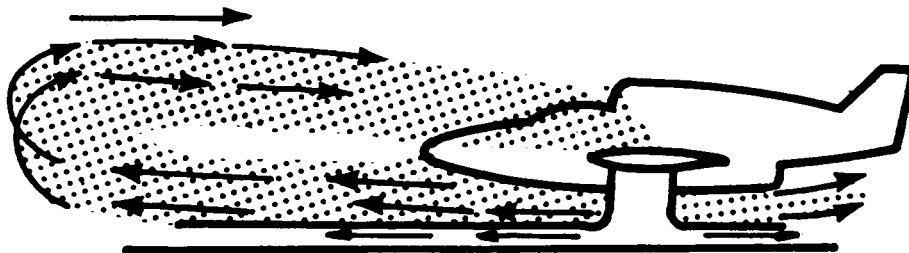
Figure 20.- Variation with airspeed of pitching moment required for trim for the ducted-fan configurations of figure 19. $\alpha = 0^\circ$. (Figure taken from reference 35.)



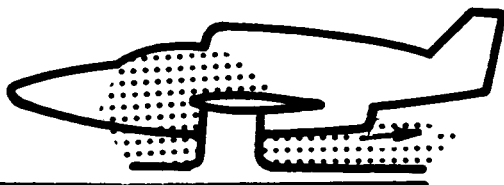
NASA

Figure 21.- Effect of ground proximity on the hovering lift of the ducted-fan configurations of figure 19. (Figure taken from reference 36.)

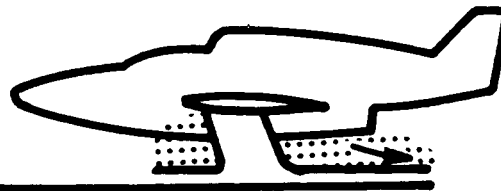
LIGHT WIND



HOVERING WITH LIGHT WIND



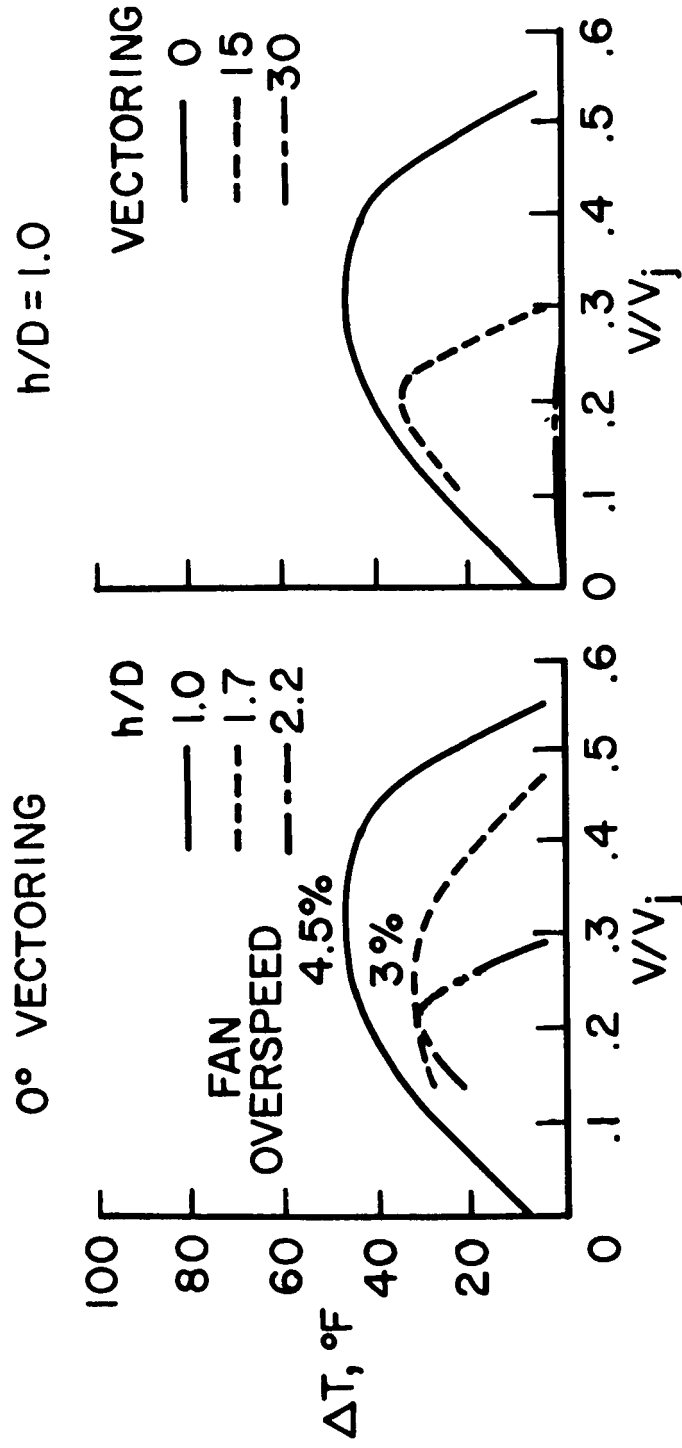
NO VECTORING,
 $V \cong 60$ KNOTS



LOUVERS DEFLECTED
 $30^\circ, V \cong 60$ KNOTS

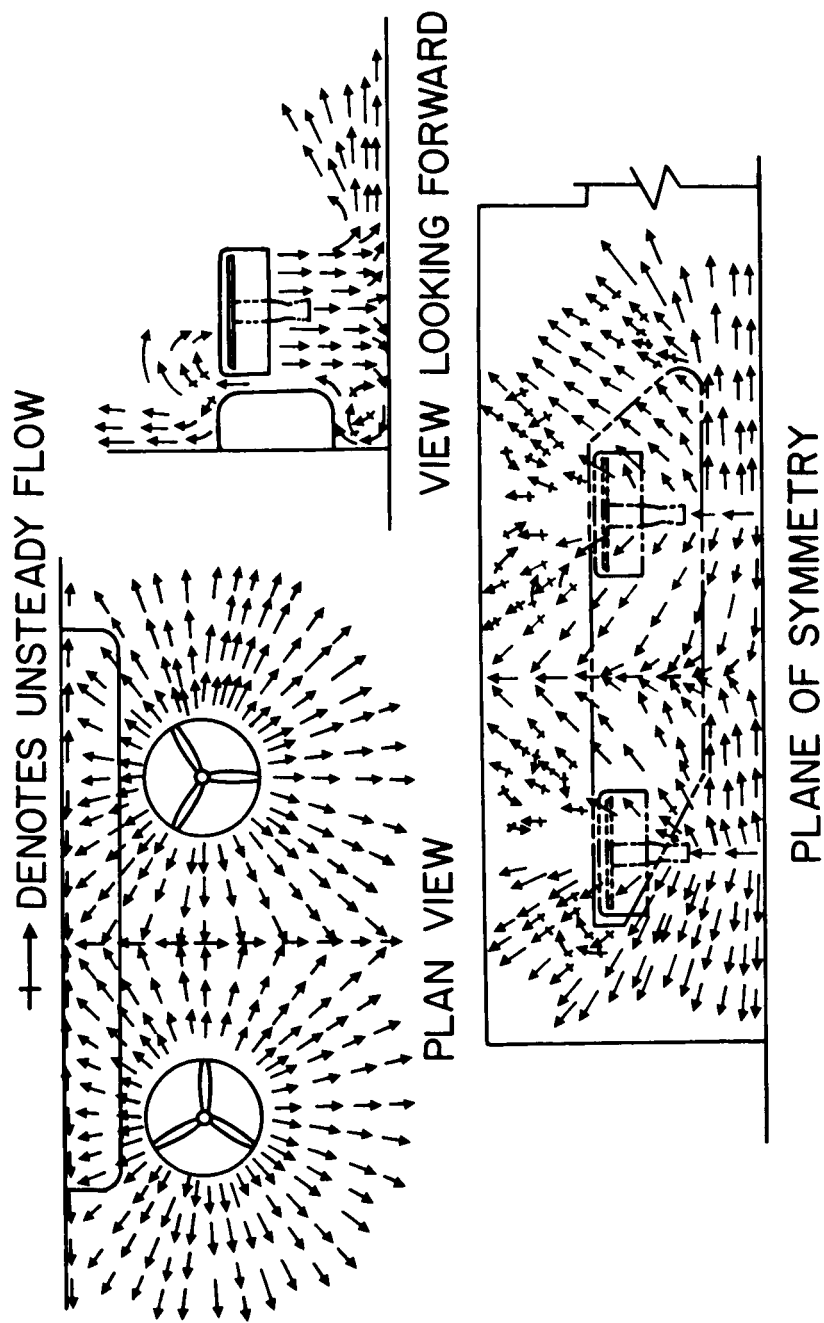
NASA

Figure 22(a).- Flow patterns in ground effect for a fan-in-wing model (model 3). (Figure taken from reference 36.)



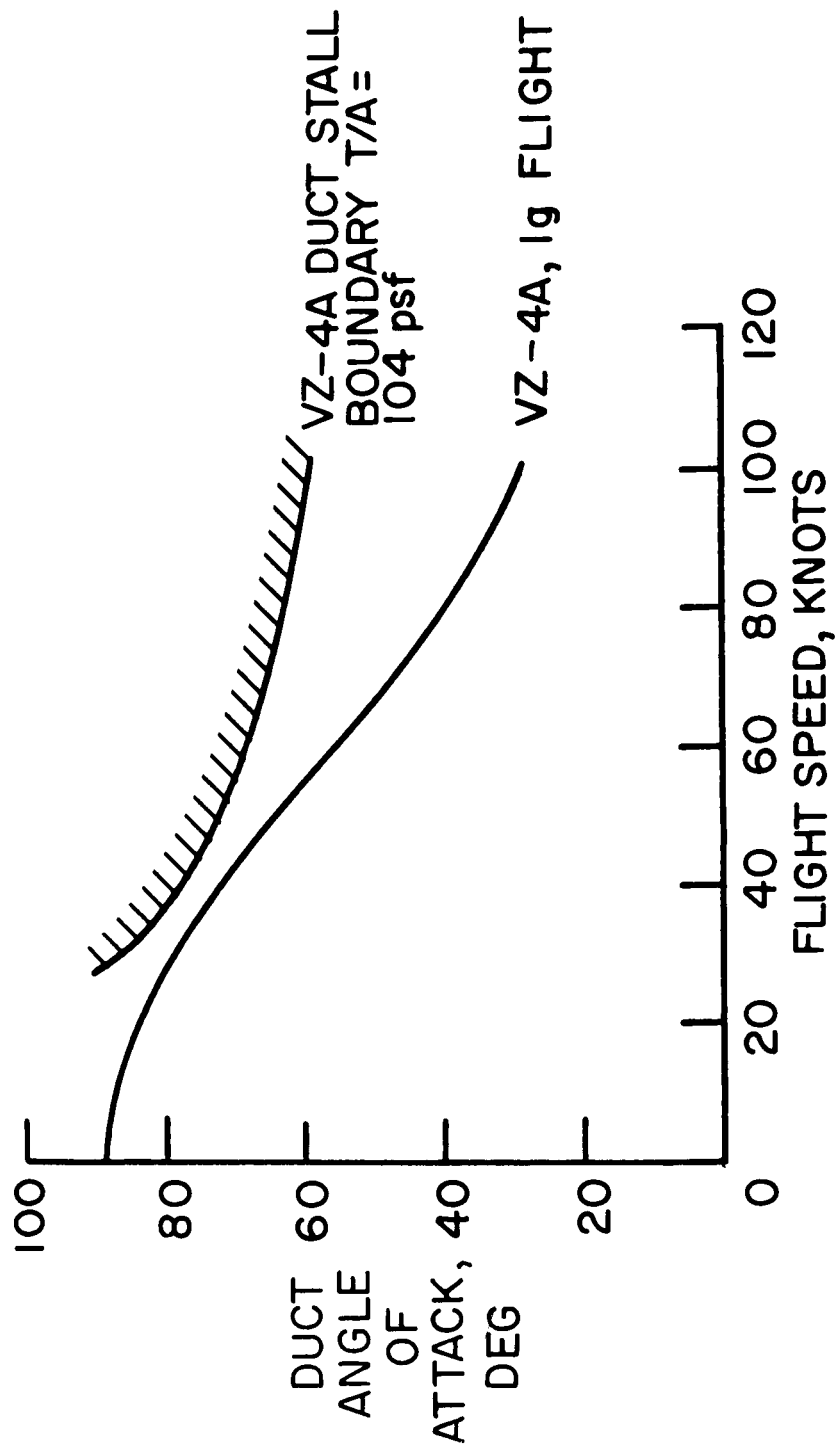
NASA

Figure 22(b).- Effect of ground height and slipstream vectoring on the temperature rise in the fan inlets of a fan-in-wing model (model 3). (Figure taken from reference 36.)



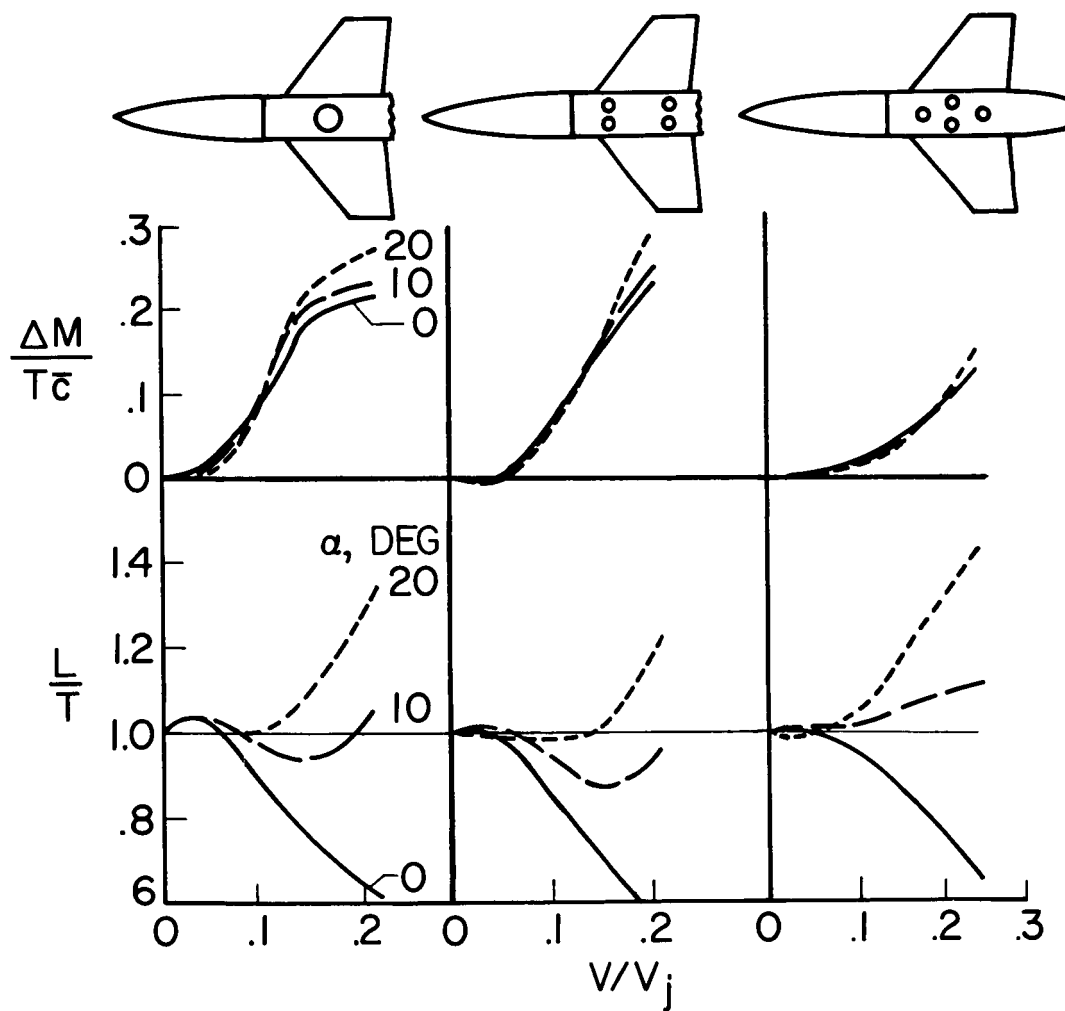
NASA

Figure 23.- Basic flow field created by the slipstreams of a four-duct tandem V/STOL configuration at a height of 1 diameter above the ground.



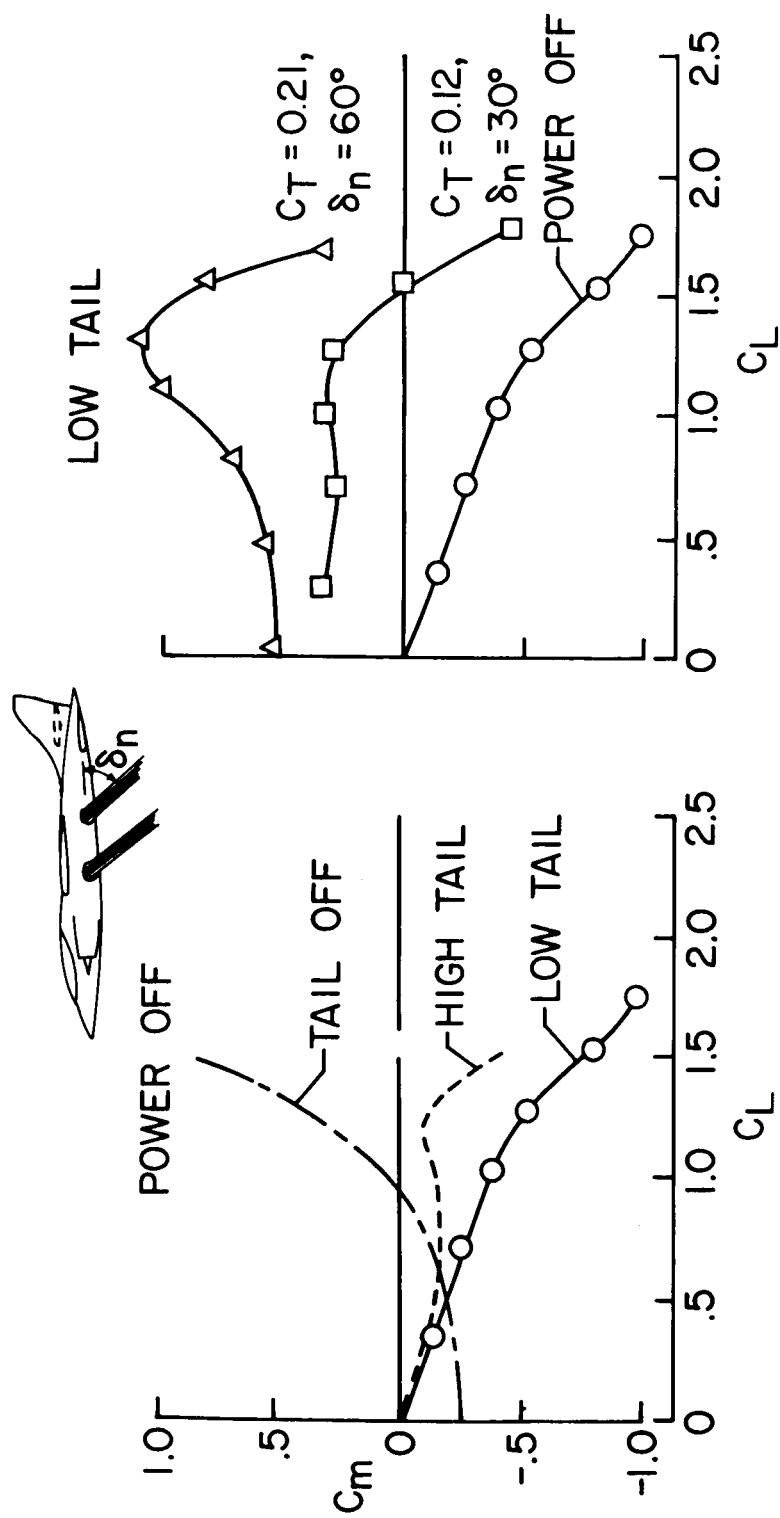
NASA

Figure 24.- Duct inlet stall boundaries in transition flight for a tilt-duct V/STOL configuration. (Figure taken from reference 36.)



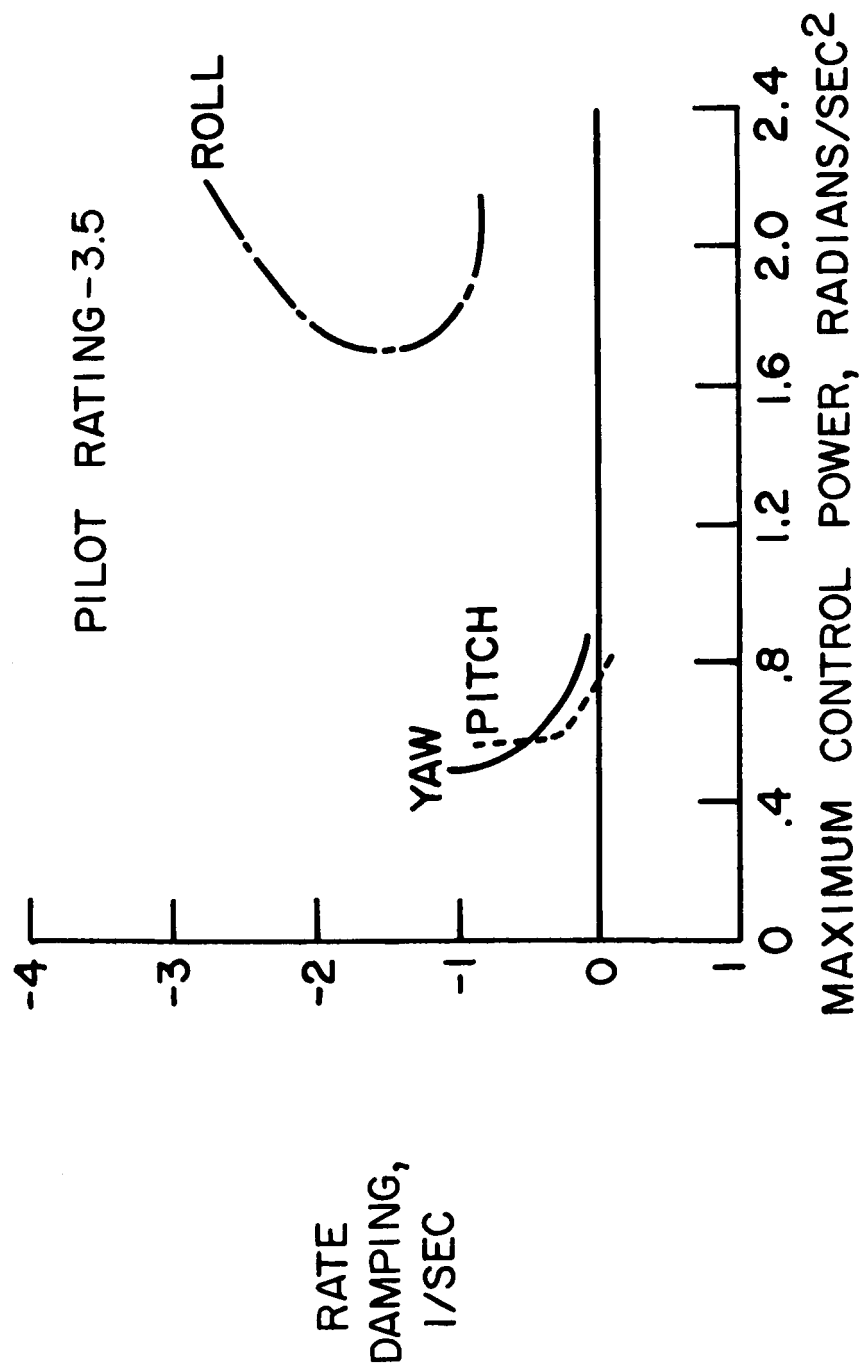
NASA

Figure 25.- Effect of nozzle configuration on the lift and pitching moment of a jet V/STOL model in transition flight.



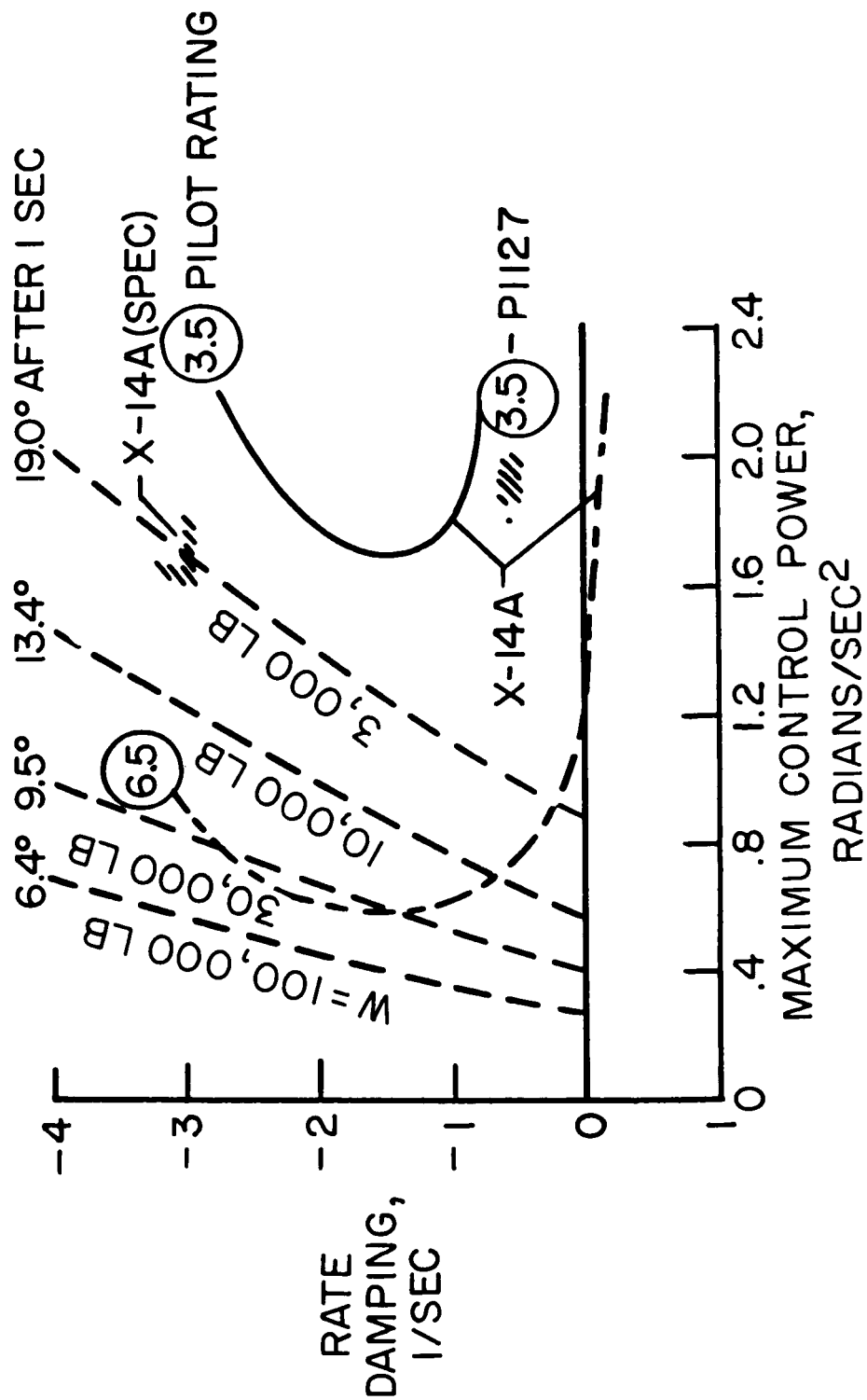
NASA

Figure 26.- Effect of horizontal-tail position and thrust on the longitudinal stability and trim of a vectored-thrust turbojet V/STOL configuration.



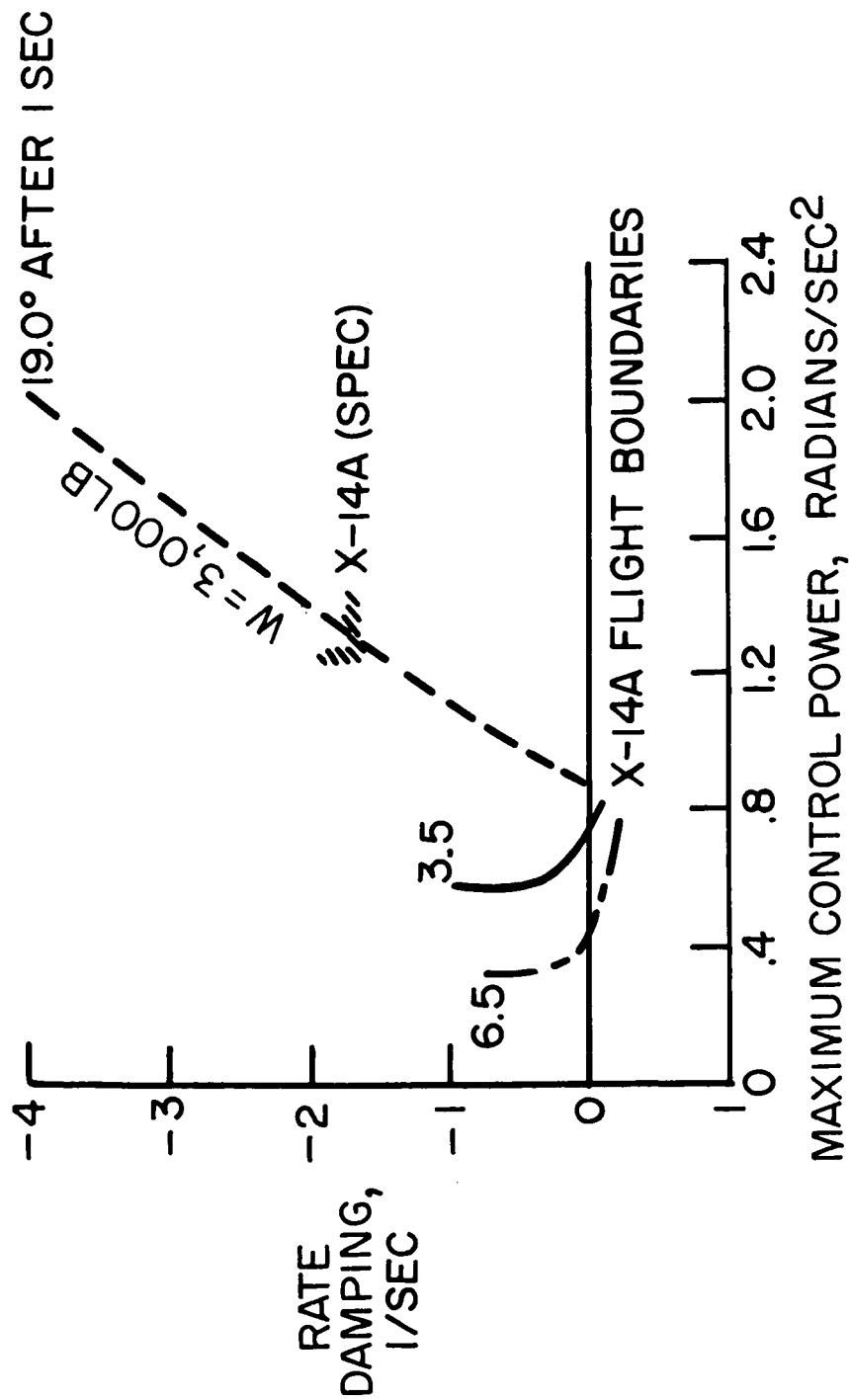
NASA

Figure 27.- Hovering control boundaries determined from flight tests of X-14A turbojet V/STOL research airplane at NASA Ames Research Center. (Figure taken from reference 57.)



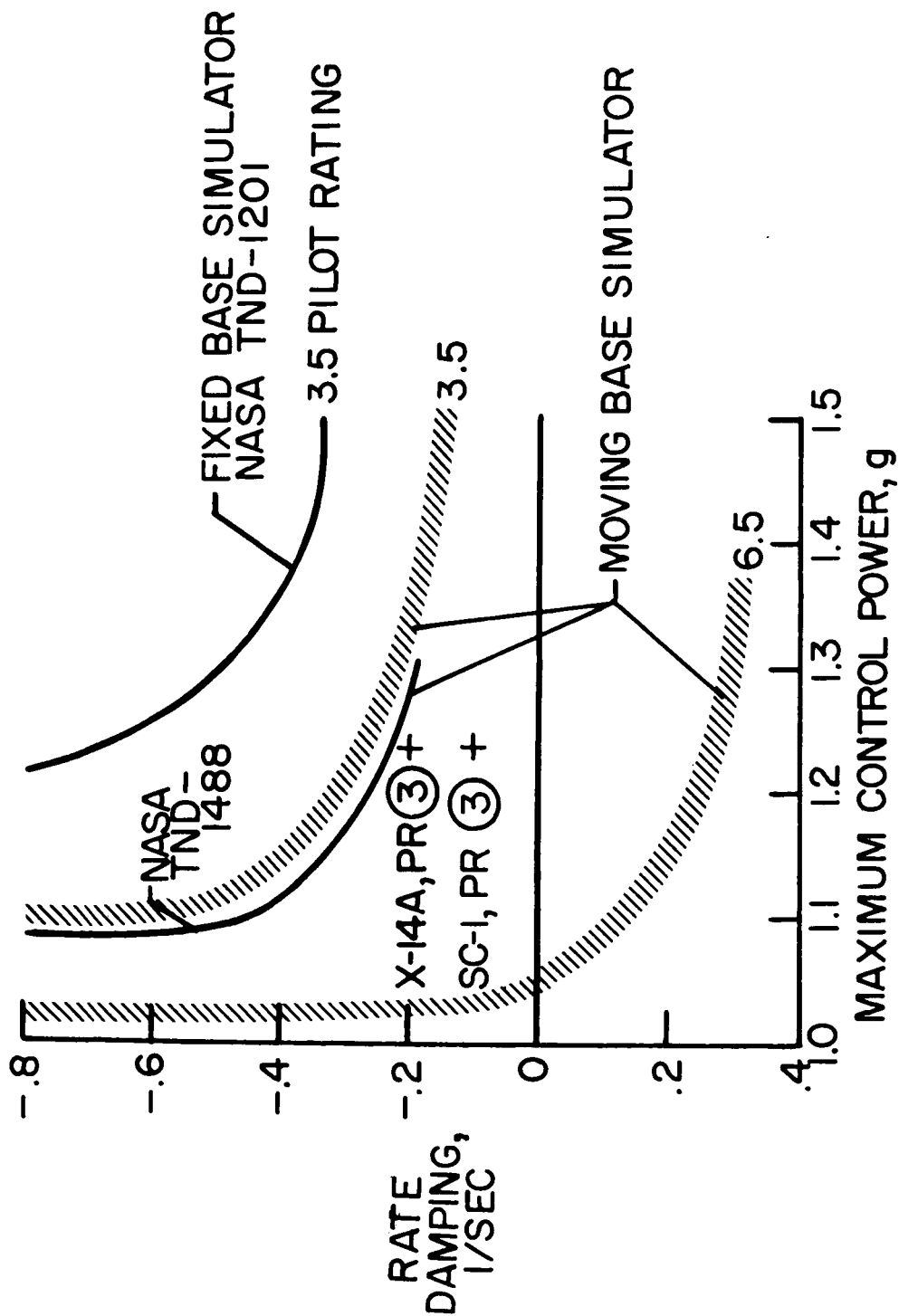
NASA

Figure 28.- Comparison of lateral control flight results from X-14A flight tests with data from other sources. (Figure taken from reference 57.)



NASA

Figure 29.- Comparison of longitudinal control flight results from X-14A flight tests with tentative AGARD V/STOL specifications. (Figure taken from reference 57.)



NASA

Figure 30.- Height control boundaries determined from flight and simulator studies. (Figure taken from reference 57.)